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A THEORETICAL AND EXPERIMENTAL STUDY OF TUNNEL BORING BY MACHINE WITH AN EMPHASIS ON BOREABILITY PREDICTION AND MACHINE DESIGN

Fun-Den/Wang, et al

Colorado School of Mines

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A THEORETICAL AND EXPERIMENTAL STUDY OF TUNNEL BORING BY MACHINE WITH AN EMPHASIS ON BOREABILITY PREDICTION AND MACHINE DESIGN

Final Report

August 1972

Prepared by

Department of Mining Engineering
Colorado School of Mines

Fun-Den Wang
Principal Investigator

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Research Assistant

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13. ABSTRACT

This report discusses the results of the first year of a proposed three year program. The three year program was to perform small and full size linear cutting tests to determine scaling factors relating thrust, torque, specific energy, and cutting coefficient for two linear rock cutting machine sizes used. Also to be studied would be the relative efficiency of various cutter types, particularly roller versus pick type cutters.

The main objective of the first year of the contract was the construction of the full size linear cutting machine. Construction and initial testing was successfully completed.

During construction of the large linear cutting machine, testing continued using a small scale linear cutting machine on samples from the Nast, Lawrence, and Climax tunnels. The results of that testing are presented here.

An extensive literature survey was undertaken, providing much valuable information relating to the problem of rock boring, and providing direction for future research.

Details of illustrations in this document may be better studied on microfiche

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SUMMARY

This report discusses the results of the first year and a 6 month no cost extension of a proposed three year program. The three year program was to perform small scale and full size linear cutting tests to determine scaling factors relating thrust, torque, specific energy, and cutting coefficient for the two cutting machine sizes to be used. This information is needed if field boreability predictions are to be made from tests performed on the exploratory cores (NX or 6 in.) taken from along a proposed tunnel alignment. In addition to the laboratory tests, actual field boring data would be collected which would aid in checking the laboratory-developed scaling relationships.

Also the possibilities of using different cutter designs would be investigated. The large linear cutter would be capable of using many different cutters. Of particular interest was the comparison of rock cutting by the more conventional roller cutter and the pick type of cutter.

The main objective of the first year of the contract was the construction and debugging of the full size linear cutting machine. The machine was to conform to the following specifications:

(a) Capability of operation in both a constant thrust mode or constant penetration mode.

(b) Maximum thrust in constant thrust mode of 25,000 lbs.

(c) Maximum cutter speed 40 inches per second.

(d) Capability of installing various sizes and types of cutters.

(e) Maximum horizontal travel of 3 feet.

All of these requirements were mét or exceeded. A list of all the machine characteristics and capabilities is provided in the section of this report on Machine Design.

Design and fabrication of the large linear cutting machine was accomplished early. However, there was a considerable delay in the cutter becoming operational due to late delivery of the horizontal actuator and controls. This delay upset considerably the time table for beginning tests using the large machine. During this delay, however, other aspects of the research continued. Further testing using the small scale linear cutting machine was accomplished, in addition to a continuing search and analysis of the literature. Testing was suspended for a month to make various improvements in the small linear cutting machine. New load transducers were installed to increase the output. This had the effect of simplifying the electrical circuitry, requiring less amplification and resulting in very improved noise characteristics.

During the first year then, the work on this contract was centered in three main areas:

(1) Design, fabrication, and testing of large scale linear cutting machine.

(2) Tests of rock samples from various actual tunnel boring sites using the small scale linear cutting machine.

(3) A continued and comprehensive literature survey of material pertinent to tunnel boring and rock cutting.

Construction of the large linear cutting machine is complete. Initial samples have been cut both for testing of the machine and calibration of the load cells. Vertical loads to 50,000 pounds have been experienced and the system functioned perfectly. Extensive testing using this apparatus should be able to proceed without difficulty.

The small linear cutting machine was used to cut samples from the Nast, Lawrence, and Climax tunnels. Characteristics of the small linear cutter can be found in the section on laboratory testing. From the laboratory experimental results the following quantities were calculated:

1. Average horizontal and vertical forces,
2. Actual penetration,
3. Specific energy,
4. Average cutting coefficient,
5. Cutting size distribution.

By use of an analog-digital computer, the following quantities were determined continuously along the length of a cut:

1. Cutting coefficient,
2. Work done.

In addition to the laboratory tests, actual field boring data was collected from the tunnel boring sites. Using this data, the above quantities were determined and compared to laboratory results.

Recently, the cutting records from laboratory tests have been analyzed with respect to frequency; that is, the frequency of force variations of different magnitude along the cut. It is felt that these force variations correspond to chipping of the rock. Frequency analysis is important both for a complete description of the behavior of rock when cut, and also in selecting the best operating conditions and type of cutter to be used. For example, in material showing very large, closely spaced force variations, the pick type cutter might not be applicable. The resulting cutter chatter would result in carbide chipping rather than a more even abrasive wear.

The most dramatic result of the laboratory study was the effect of structural features and rock weaknesses in the cutting of rock. This indicates that machine design should make better use of these weaknesses for more efficient rock removal.

As is expected, the laboratory values of specific energy were higher than field values. Since specific energy is a good indication of the boreability of a particular rock type, it is essential to develop the scaling relationships that relate laboratory specific energy values to field values. Certain definite relationships are shown which indicate the need for a better knowledge of the particle size of cuttings and the structure of the rock to be bored.

The inverse relationship between specific energy and cutting coefficient, both in the field and in the laboratory, supports the idea that machine design should try to increase cutting coefficient to obtain better boring results. Present machine design puts a definite limit on the cutting coefficient. Increasing the depth of cut increases the width of cut and also the size of cuttings. This would result in lower specific energy and reduced cutter wear per volume of rock removed.

During the course of this contract an extensive search of the literature was carried out. Areas of interest relating to rock boring were investigated, such as:

1. Independent cuts with roller and pick cutters.
2. Multiple and dependent parallel cuts with roller and pick cutters.
3. Static bit penetration tests.
4. Dynamic fracturing of rock.
5. Stress distribution and rock behavior under various bits and cutters.
6. Effects of cutter types and penetration on specific energy.
7. Optimum indexing-penetration ratio for various cutter-rock combinations.
8. Effect of boring rate and/or speed of cutting.
9. Effect of rock properties.
10. Scaling relationships.

The literature has provided valuable information related to the problem of rock boring. Much progress has been made toward an understanding of rock failure under cutters. However, as yet no one has been able to relate this information to prediction of field boring performance. Also, even with the apparent differences in efficiencies of the different cutter types, no meaningful and direct comparison of the applicability of the respective types has been made to date. It appears the best way to eliminate this gap in the knowledge is through extensive tests with the small and large scale linear cutting machines and by using various cutter types for these tests.

It is apparent that much work still needs to be performed in the areas of boreability prediction and machine design. Here at the Colorado School of Mines we are ideally equipped and staffed to provide this needed research. It is hoped that in the near future, meaningful boreability predictions can be made from small core from along a proposed tunnel alignment; also to be able to make recommendations as to best cutter type and operating parameters for a particular boring situation.

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PART I

DESIGN AND CONSTRUCTION OF LARGE LINEAR CUTTING MACHINE

1. INTRODUCTION

Early attempts (14) at comparing small scale linear cutting results with full scale cutting data indicated that the only way to consistently have available full scale cutting data on similar rock was to build a large linear cutting machine that would be capable of simulating field boring loads and conditions. The major part of our effort this past year has thus been to design and build a large scale linear cutting machine. Research contract requirements called for the following capabilities:

1. Capability of operation in constant thrust mode or constant penetration mode.
2. Maximum thrust in constant thrust mode 25,000 lbs.
3. Maximum cutter speed 40 inches per second.
4. Capability of installing various sizes and types of cutters.
5. Maximum usable horizontal travel of 3 feet.

Construction of the large linear cutter is now complete. Delays beyond the expected completion date were a result of late delivery of the servo-controlled horizontal positioning system. Testing has begun on initial samples of sandstone. Cuts of 1/2 in. penetration have been made with resulting vertical loads of up to 50,000 pounds, and all components have worked quite well. Some initial results have been obtained for comparison to data from the small linear cutting machine.

2. DESIGN

The contract specifies that the large linear cutting machine should be capable of being operated in either a constant force or a constant penetration mode. The constant force mode is accomplished simply by providing the hydraulically powered vertical force ram with a nitrogen accumulator that maintains an essentially uniform pressure to the ram, thereby maintaining constant force to the cutter as it traverses the rock.

The constant displacement mode is considerably harder to accomplish. One must maintain a uniform depth of cut even with wide variations in vertical force as the cutter passes alternatively over hard and soft sections of the rock. Since the depth of cut is fixed, one needs then only force variations which is quite easily accomplished using strain gage instrumentation. It is felt, furthermore, that the constant displacement operation better represents the action of an actual boring machine. Ideally, the cutter should be mounted to an infinitely rigid frame, and the rock should rest on an infinitely rigid base. This is, of course, not practical and a maximum allowable deflection must be determined. The linear cutter is then designed to conform to this limit.

For the linear cutting machine at the Colorado School of Mines, a maximum deflection of 0.01 in. was chosen as a practical limit. Each part of the system must then be designed as rigidly as practically possible.

A 3 ft deep concrete base heavily reinforced with No. 8 and No. 10 steel reinforcing bars was poured in the floor of the Mining Engineering Research Lab to provide a solid base and limit deflections from the anchorage. The slab also provided the means to keep all forces within the system. The frame for holding the cutter consists of two 36-in. wide-flange columns and a crossbeam consisting of two 18- by 8-in. wide-flange beams and two 18- by 4-in. channels welded together to form an 18- by 24-in. box beam. With the loads to be used, the deflection in each of these members is approximately 0.001 in. The saddle holding the cutter is moved up and down by a 50,000-lb-capacity ram. Steel spacers placed between the beam and the saddle are used to hold the cutter rigidly at a particular depth of cut. The deflection in the cutter mount is comparable to mounts found in commercial use. The vertical ram used on the cutter has a servo-controlled valve allowing programming of the vertical load.

Loads on the cutter are measured by load cells similar in concept to stress bolts. The bolts and the strain gages on the bolts are situated to produce maximum output and cancel any bending or torsional effects.

The horizontal translation of the rock under the cutter is accomplished by a servo-controlled hydraulic actuator. The actuator is capable of producing a stall force of 55,000 lbs and a dynamic force of 30,000 lbs at a velocity of 40 in. per second. The back of the actuator is mounted on a 3- by 2- by 2-ft concrete block which is, in turn, anchored 3 ft into the base previously described with two 5-in. wide-flange beams and No. 10 reinforcing bar. The horizontal actuator is controlled by a function generator and controller that provides a full range of velocities from zero to 40 inches per second and higher. The hydraulic power is supplied by a 20-hp, 20-gpm standard power supply. The power supply is equipped with two nitrogen-pre-charged piston accumulators to provide the flow necessary to supply the actuator at high speeds.

The platform upon which the rock is carried was fabricated from 5-in. wide-flange beams and 1/2-in. plate. The platform slides along 3-in. centerless-ground 60-Rockwell-C-case-hardened shafts supported every 12 in. to eliminate bending. The bearing consists of a solid block of aluminum having a 3-in. hole cut to fit the shafts. Four bronze-impregnated teflon rods 3/4 in. in diameter and 8-in. long are situated around the circumference of the 3-in. hole and are cut to provide a bearing surface and to keep the aluminum out of contact with the shafts. The frame for holding the rock was constructed by stacking 5-in. wide-flange beams horizontally to form a box of inner dimensions 3 by 3 1/2 ft.

The reason for such heavy construction is to provide the capability of installing flat jacks which would allow the application of a biaxial stress field to the specimen, simulating underground loading. Shields to prevent dangerous flying chips have been installed.

Due to the possible danger of the powerful units involved in the operation of the linear cutter, a special room providing limited access was constructed around the apparatus.

A summary of the large scale linear cutting machine's capabilities and characteristics follow:

1. Allows the use of full-scale cutters.

2. Can be adapted to any conventional rotary cutter with only minor changes in cutter mountings.

3. Will allow the use of pick type cutters.

4. Can handle manufacturer suggested allowable cutter loads.

5. Allows vertical loads to 25,000 lbs with only 0.01 in. deflection of cutter.

6. Capable of much higher loads safely, but with a corresponding increase in deflection.

7. Horizontal force to traverse rock under the cutter is up to 55,000 lbs, depending on speed.

8. Full range of speeds available to cover all speeds found on conventional boring machines.

9. Strain gage instrumentation is fully compensated for bending and temperature and allows analysis of all pertinent cutter forces such as vertical, horizontal, and side force, and including torque on the cutter bearing shaft.

10. Can operate in constant penetration mode or constant force mode.

11. Lateral confining pressures can be applied to the sides of the specimen to be cut.

12. Any required depth of cut is easily set.

13. Any required indexing is easily set by lateral translation of the specimen.

14. Capable of a 45 inch stroke under cutter.

15. Can handle samples to 3 1/2 ft long by 3 ft wide by 3 ft deep.

Pictures of the cutting machine are shown in Figures 1.1 through 1.4.

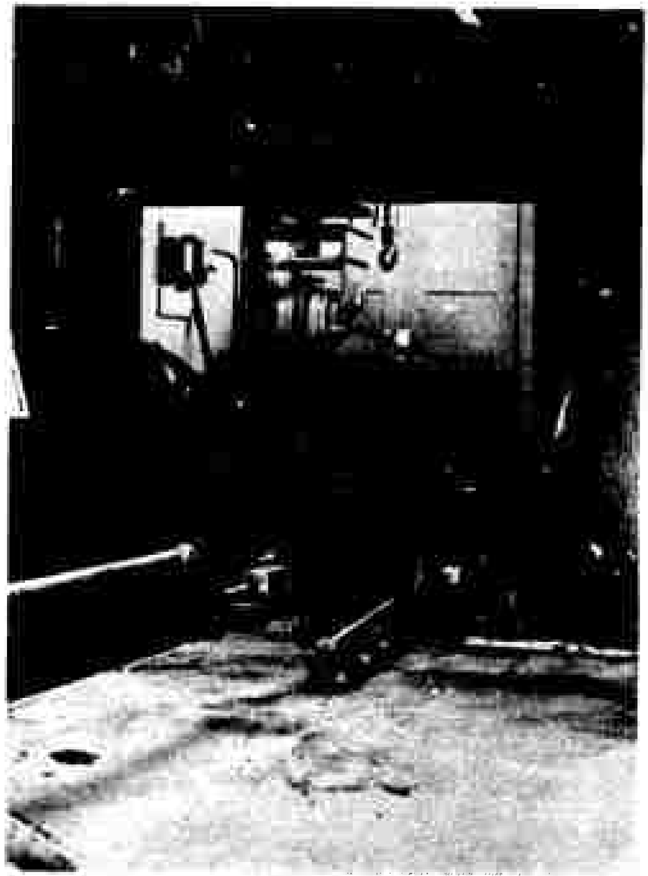

Fig. 1.1 Overall view of the linear cutting machine showing the frame, the rock carriage and guides, the saddle, and the cutter.

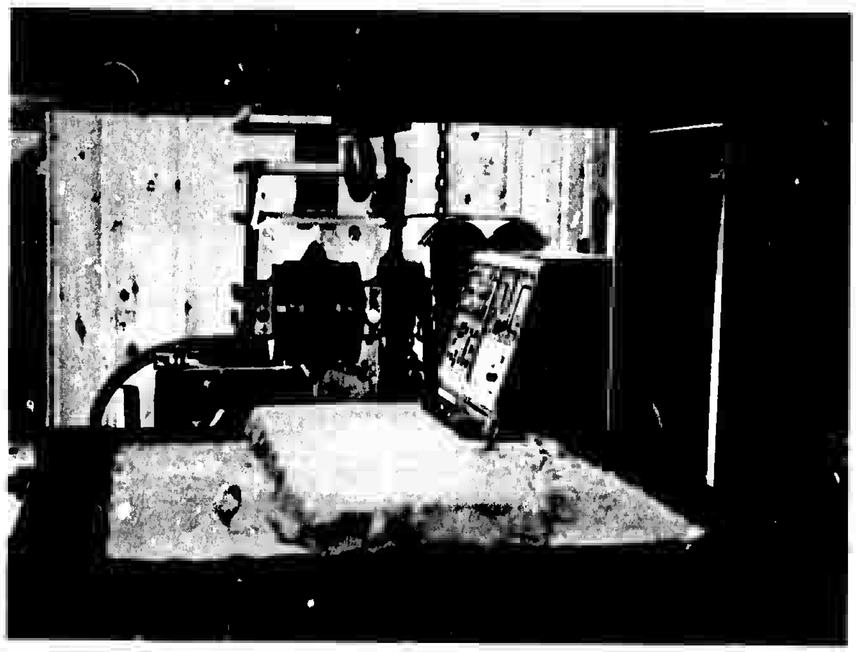

Fig. 1.2 View showing the cutter head and the rock block mounted in the carriage.

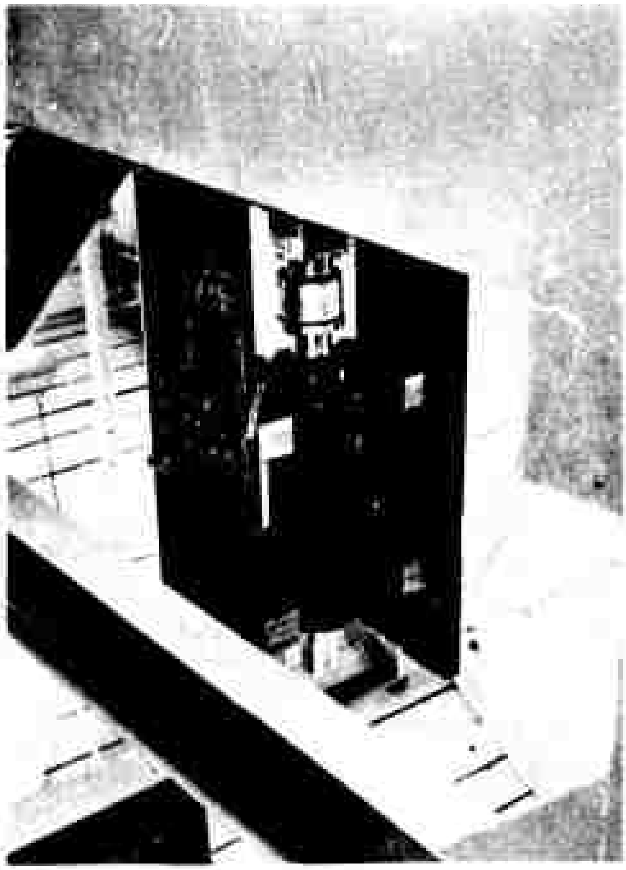

Fig. 1.3 View of the ram for running the tests in the constant thrust mode.

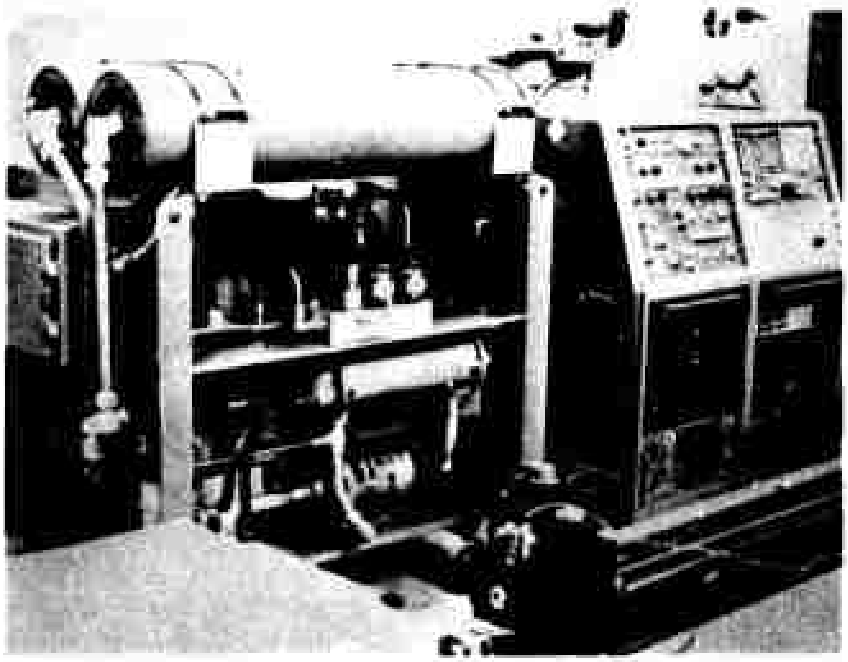

Fig. 1.4 MTS Power Supply, the servo controller for the vertical ram, the actuator for driving the rock under the cutter.

PART II

SMALL LINEAR CUTTING RESULTS, SOME ACTUAL TUNNEL BORING RESULTS, AND THEIR ANALYSIS

1. INTRODUCTION

Tunnel boring machines using mechanical cutters have improved greatly during the past few years and it is now possible to cut very hard rocks. The question that remains, however, is whether the rocks can be bored economically. Presently, at least for medium to hard rocks, this question is sometimes only answered after a very expensive lesson of using and then removing an inappropriately chosen (or used) machine. The fact that such costly mistakes do happen reflect our present inability to make reasonable performance predictions on the basis of the small samples available before the tunnel is begun. Since the sample size is generally small, the number and variety of tests that can be used is rather small. In the past, generally only physical property data such as the uniaxial compressive strength, Young's modulus, etc. and perhaps small hand samples have been available on which bids were to be made. Over the past several years the CSM Mining Department has developed a small linear cutter that can be used to cut these samples and provide some information regarding the forces and energies required. At present, unfortunately, the scaling relationships required to translate these forces and energies into full scale are not available. The relationships, however, can only be developed by comparing the laboratory and field boring results in a manner similar to that discussed in this report.

In this part of the report the results of tests in which the small linear cutter was used to cut samples taken from the Nast, Lawrence, and Climax tunnels are described. Field boring data is also given for the Nast and Lawrence tunnels. A comparison of laboratory and field results is made and the difference discussed.

2. EXPERIMENTS

2.1 Laboratory Testing

2.1.1 Linear Cutter

The small linear cutter used in this project is shown in Fig. 2.1. As can be seen, the cutter head is mounted to an old milling machine. The design force limitations are 7000 lbs vertical and 3000 lbs horizontal. The operational loads were generally below these design limits. In testing a few samples the peak values approached the maximum limit of vertical force, and therefore the cutter support system should be as rigid as possible. The testing method employed requires constant displacement. The maximum horizontal force is limited by the power output of the milling machine motor. With higher force levels it may not be powerful enough to maintain constant table speed.

For the highest loads the stiffness of the horizontal support arms of the unit was barely adequate. This can be observed in some of the records by the presence of elastic rebound force. This occurs when the cutter, after high horizontal loading, reached a hole in the sample where the horizontal component of the rock reaction is zero. The stored elastic energy in the support system is then released causing the arms to go momentarily into tension. This effect can be seen in some of the curves of the horizontal force.

This rebound effect does not significantly affect the average results. It does affect the value of the cutting coefficient (the ratio of horizontal to vertical

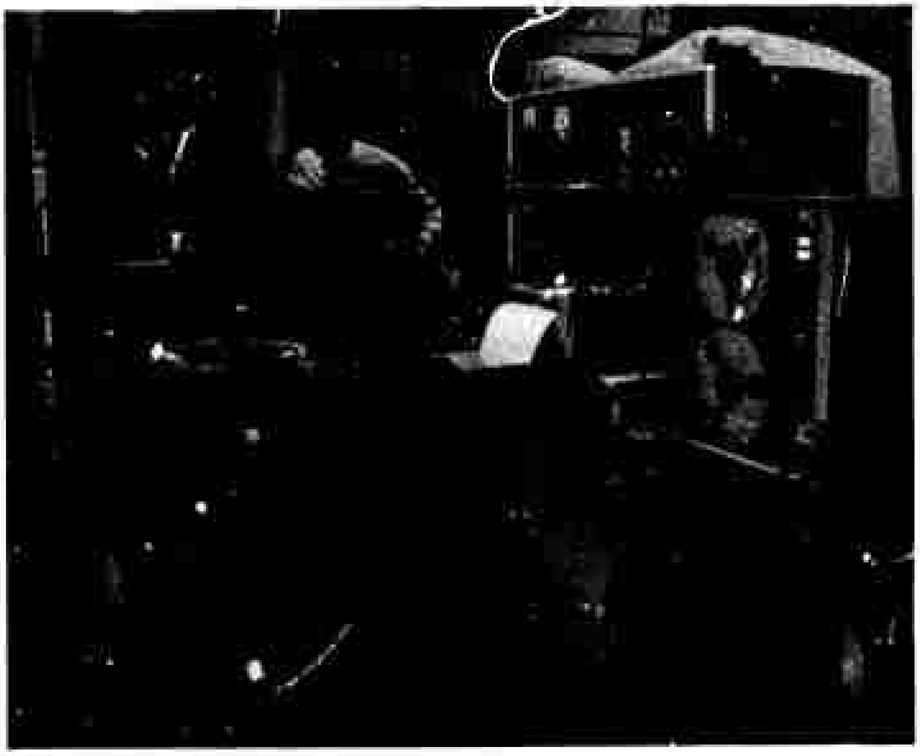

Fig. 2.1. Linear cutter unit in the laboratory.

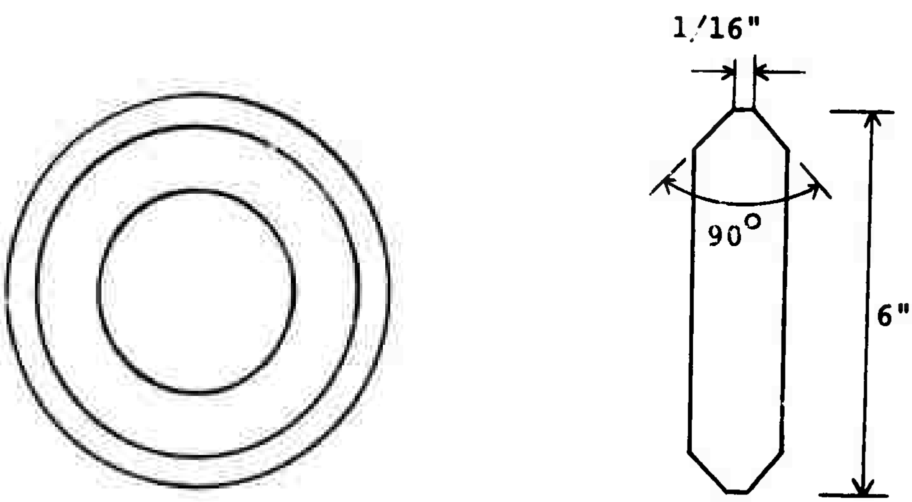

Fig. 2.2. Disk type kerf cutter used in the laboratory.

force) although the effect is felt only over a short distance. It has practically no effect on the calculated total energy along a cut.

The design of the cutting unit is such that cutters of different diameters and types may be employed. The cutter unit is constructed of mild steel except for the cutter which is made of Ketos steel (Crucible Steel Co., type AISI 01). The cutter was hardened to 58-62 Rockwell hardness after machining and then ground to a final cutting edge having a 90° included angle. The cutter is 6 inches in diameter and 1/2 inch thick, and has a 1/16 inch wide wear flat on the cutting edge. A diagrammatic representation of the cutter is shown in Fig. 2.2. This cutter was used throughout the tests. The controls of the milling machine allowed for accurate ($\pm$.002 in.) settings of penetration and indexing.

2.1.2 Instrumentation

The instrumentation was modified from that used earlier with the linear cutter system to include recording on magnetic tape. The tape was used as the input to the hybrid computer. The signals from the vertical and horizontal arms had to be amplified for input to the tape. The circuit is shown in Fig. 2.3.

Strain gages (120 ohm, G.F. 2.04, type SR-4) mounted on two sides of the restricted sections of each of the support arms were connected in series to compensate for any bending. A constant voltage of 10 volts was maintained across the Wheatstone bridge circuit. The sensitivities were 4410 lbs/mv for the vertical and 3310 lbs/mv for the horizontal arms. Temperature compensating gages

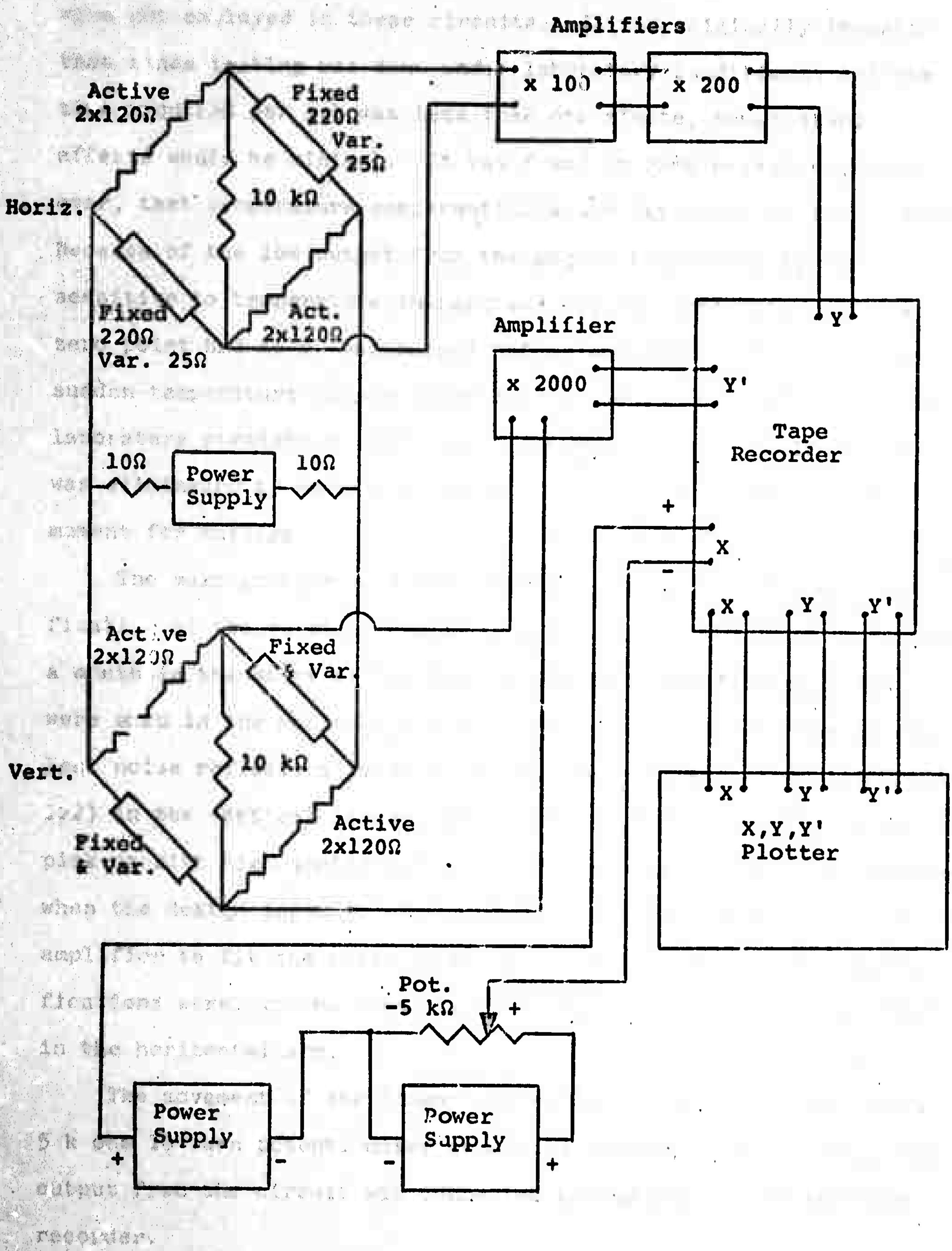

Fig. 2.3. Circuit diagram for the strain gages used in the small linear cutting machine.

were not employed in these circuits. It was originally thought that since testing was done under laboratory conditions, and the time required per cut was less than one minute, temperature effects would be minimal. It was found on some occasions, however, that temperature compensation would have been an improvement. Because of the low output from the gages, they actually were sensitive to temperature changes and careful observation of the zero point had to be maintained before and after each cut. The sudden temperature changes were due to opening of a door from the laboratory straight to the winter weather outside. This effect was eliminated by careful checking of zeros and by choosing the moment for cutting.

The main problem in the electrical circuit was in the amplification of the vertical signal. This caused a delay of more than a month in the start of the tests. The Dana amplifiers, which were used in the horizontal circuit performed well and had excellent noise reflection levels. A new Honeywell amplifier (ACCUDATA 122) in the vertical circuit caused us trouble due to the noise pick up with high amplification. This problem was finally overcome when the design engineer of the amplifier made some changes in the amplifier to fit the noise problem in the laboratory. The amplifications were, in the final tests, 2000 in the vertical and 20,000 in the horizontal arm.

The movement of the linear cutter table was monitored with a 5 k ohm 10 turn potentiometer connected to balancing circuit. The output from the circuit was connected to one channel of the tape recorder.

Three channels were used in the tape recorder (Honeywell 8100): one for displacement, one for vertical force, and one for horizontal force. The tape recorder was calibrated to -2 volts to +2 volts peak to peak value. Hard copy records were made by playing the tape into an XYY' recorder. For the calibration of the output from the tape, calibration voltages were put at the beginning of each tape. The tape was then used to provide the input to the hybrid computer.

2.1.3 Sample Preparation

All the samples used from the Climax tunnel were in the form of 6 inch diameter cores. The samples from Nast and Lawrence tunnels were taken from blocks. The cores were sawed in half lengthwise and one half was used for cutting and the other half to prepare samples for the physical testing.

The core halves and the samples which were sawed from the blocks were mounted in a channel iron mold and surrounded with hydro-stone. After the hydro-stone had set at least twelve hours the surface of the samples were ground to the smoothness of ±.003 inch using a surface grinder. The smooth surface was necessary to assure reproducibility of results and to provide an accurate reference for volume measurements. After drying 48 hours at room temperature, the samples were clamped into a support frame on the table of the linear cutter and checked to insure a level of the surface. Testing could then be commenced.

2.1.4 Testing Method

After a sample was prepared and mounted on the machine, a testing procedure was established depending on the sample properties.

To eliminate "end" effects the first 1 1/2 inches and the last 1 to 2 inches of the cut were marked out and not included in the area and volume measurements. The samples were cut through from one end to the other.

Rather than a constant vertical force, a fixed penetration depth was set on the adjustable mobile table. The penetration depth was set when the cutter was free of the rock sample so that each force-displacement recording began with a zero vertical and horizontal force. The starting point of the table movement was set a sufficient distance ahead of the point of contact with the sample so that a zero load recording could be obtained on the tape for the setting of the zero in the hybrid computer.

The indexing was fixed to 0.30 in. in all tests, except in the last pass in the sample Climax #7. In hard rocks this indexing was too wide to cause breaking between the cuts on the first pass; it was, however, adequate for successive passes. The indexing was not taken as a variable in these experiments because it was understood that indexing was constant in the tunnel boring machine, and because the comparison is made between laboratory results and field data.

In this report a cut means one linear indentation along the surface of the sample. A pass is defined as the removal of one layer of rock resulting from several indexed cuts. The first pass consisted of eleven cuts on the 6" core samples which left 1.5 in. wide area on both sides which was not cut. At least as wide an area was left on the sides of the narrower samples when only seven or nine cuts were cut on the first pass. To minimize the effect of confinement on the results the outer two lines were dropped after each volume measurement from the next pass. Because the last pass consisted in each case of at least three cuts, two consecutive passes had the same amount of cuts on some samples.

The set penetration for different passes could be maintained constant only for hard samples. It was necessary to vary the penetration for softer rock to compensate for the overbreak from the previous passes and to obtain a relatively equivalent force curve for all passes. The set penetration in hard rocks was usually 0.030 in. but was increased up to 0.120 in. in soft rock.

To determine the specific energy (the energy required to break a unit volume of rock), it was necessary to measure the volume of the removed material. It had been found earlier by Ross (1) that it was impossible to determine the volume of an individual cut and therefore a system was established to measure the volume of an entire pass. Ross compared different ways of measuring the volume (volume displacement of cuttings, sand filling, molding silicone rubber and cross section profile measurement), and concluded that sand filling was fast, as accurate as the others, and readily adaptable to the variations in the cuts.

Dry sand was used in this work for volume measurement. Sand of screen sizes -65/+150 mesh was used. The missing ends of the craters were replaced along the marked lines using ordinary putty. The top of the crater was planed with a rigid straight edge using the ground surface of the rock sample as a guide. The volume of sand was determined using a graduated cylinder. Because the volume of sand depends on the packing and because the sand-filled crater was almost unpacked, the volume of sand was taken to be the value which was obtained when sand was poured into the cylinder without any more packing. Because errors may easily result in hasty volume measurement, much care was put into performing the determination consistently each time. To eliminate the occasional errors the measurements were repeated.

2.2 Calculation of the Laboratory Results

From the laboratory experimental results the following quantities were calculated:

1. Average horizontal and vertical forces.
2. Actual penetration
3. Specific energy
4. Cutting coefficient
5. Cutting size distribution

By the analog-digital computer the following quantities were determined continuously along the length of a cut:

1. Cutting coefficient
2. Work done

2.2.1 Average Forces

To get the average horizontal and vertical forces, the areas under the marked portions of the recorded force versus displacement curves were determined using a planimeter. Dividing this area by the marked length we obtained the average forces for each cut. The average of the forces for each cut of the pass was taken as the average force of the pass.

2.2.2 Actual Penetration

The penetration, which was set on the machine, was not always the same as the actual penetration realized in the cutting. The reason for the differences is that rock did not break exactly to the depth of the set penetration; in some cases there occurred much "overbreaking" and in some cases in hard rocks the actual penetration did not reach the set penetration.

To obtain the average actual penetration for a pass, the measured pass volume was divided by the plan area of the pass between the marks on the sample. This average penetration for a pass is denoted in the results as a calculated penetration.

A calculated penetration for a given sample is the average value of the calculated penetrations for each pass made on the sample.

2.2.3 Specific Energy

The energy for each cut was determined using the average horizontal force and the distance between the marks on the sample.* As will be discussed later, the energy was also determined by a hybrid (analog-digital) computer continuously along the length of the cut.

The energies for each cut used in the marked area were summed to give the energy used for each pass. Dividing the energy used in a pass by the measured volume of the same pass we obtained a value for energy per volume. This is called the specific energy.

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*This is justified, because the displacement in the vertical direction is very small compared to the displacement in the horizontal direction. The energy from the vertical load is thus a very small part of the total energy.

The specific energy of a sample is the average value of the specific energies for each of * passes.

2.2.4 Cutting Coefficient

The cutting coefficient is defined as the ratio between the horizontal force (F_H) and the vertical force (F_V).

$$\mu = \frac{F_H}{F_V}$$

From the average values of the forces, the average cutting coefficient was determined for each cut. The cutting coefficient of a pass is the average value of the cutting coefficients of the cuts. The cutting coefficient of the sample is the average value of the cutting coefficients of the passes.

A continuous record of the variation of the cutting coefficient along the length of the sample was found using the hybrid computer.

2.2.5 Cutting Size Distribution

The cuttings from each pass were collected as carefully as possible for the determination of the size distribution. The sieving was performed using sieves from 4 mesh to 325 mesh. The results are, however, presented in a collected form.

The reliability of the sieving analysis cannot be too good as the amount of the material is small and there may be some losses of material, too. On the other hand, the results of various passes on one sample show so much consistency that some notes based on size distribution are justified.

2.2.6 Calculations in the Hybrid Computer

The hybrid computer at the University of Colorado (C.U.), Boulder, Colorado, was used to determine the cutting coefficient and energy along a cut on the sample. Dr. Donald Dick from C.U. prepared the needed programs and advised in the use of the computer.

The magnetic tape on which the cutting results were recorded was taken to Boulder where it was played back by the tape recorder and this output was fed into the analog part of the computer. The analog computer did the sampling of the data, usually taking 500 samples along the seven inch length of the sample. After sampling, the calculations were performed by the digital part of the computer. The output from the computer was then taken on an X-Y plotter.

After some difficulties at the beginning, especially with the tape recorders, the system began to work smoothly. DC calibration signals (zero, positive, and negative voltages) were recorded on each tape in the laboratory for calibration of the tape output.

The most time consuming part of the computer calculations was the plotting of the output. To complete one cut from the input of data to the end of the recording of the output took 5 to 10 minutes.

The output from the computer gave us continuous records of the cutting coefficient and total energy along the cut. The cutting coefficient was calculated for each sampling point and the output was given so that the displacement axis was scaled at a 1:1 ratio with the actual displacement on the sample. The plots show very large variations along the length of the cut.

The output of energy is given as a total energy at each point. The energy calculated for each sampling distance was added to the total energy of the preceding sampling point.

2.3 Tunnel Boring Data

Up to date tunnel boring data was received from the Nast tunnel in Colorado and to a certain extent from the Lawrence tunnel in Chicago. The promised data from the drift bored in the Climax mine arrived in February 1972 and was incomplete, so that it could not be used properly to calculate specific energies or cutting coefficients.

Data from the White Pine mine was not available at the time of this report. The first blocks for laboratory testing arrived in the middle of February, and initial testing has been carried out.

2.3.1 Nast Tunnel

The Nast tunnel is being bored using a Wirth machine, by Peter Kiewit and Sons, as part of the Fryingpan-Arkansas project for the United States Bureau of Reclamation. The bored tunnel has a diameter of 9'10" and will have a length of about 15,700 ft. The alignment and profile of the tunnel are given in Fig. 2.4 (2).

The machine is shown in Fig. 2.5, and the cutting head in Fig. 2.6. In the picture of the cutting head, four bits are absent. The cutters were tungsten carbide button bits. For a short distance disk type cutters were tried in porphyritic type granite, but they were removed as the boring rate was not improved. This was not

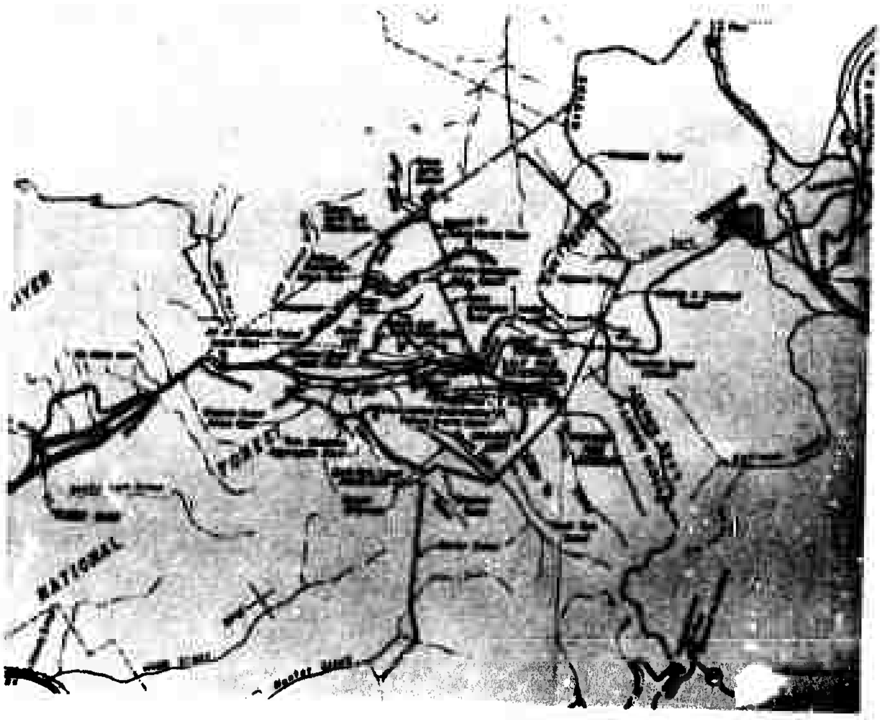

Fig. 2.4. Alignment and profile of the Nast tunnel.

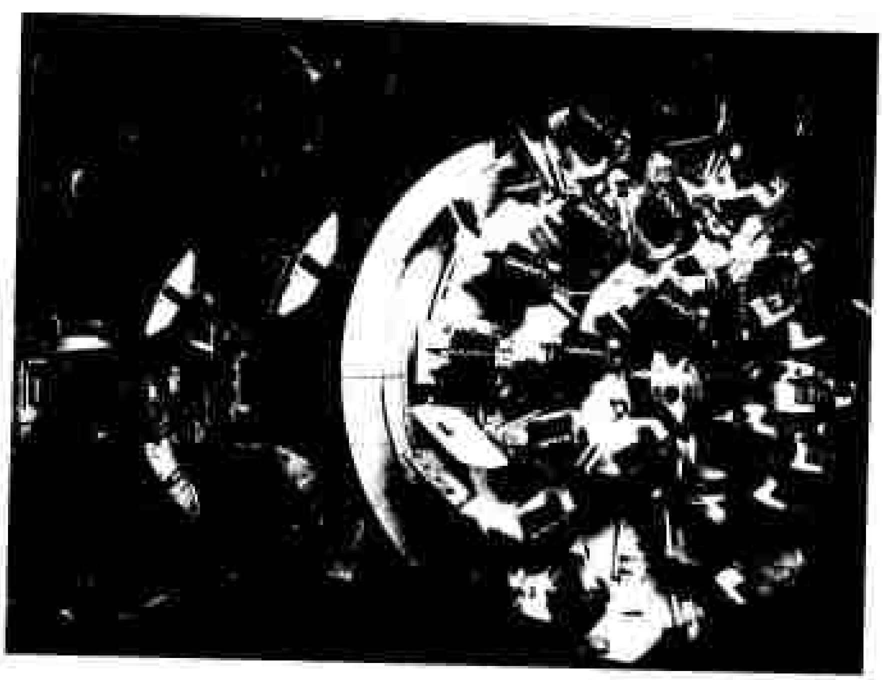

Fig. 2.5. The Wirth boring machine used in the Nast tunnel.

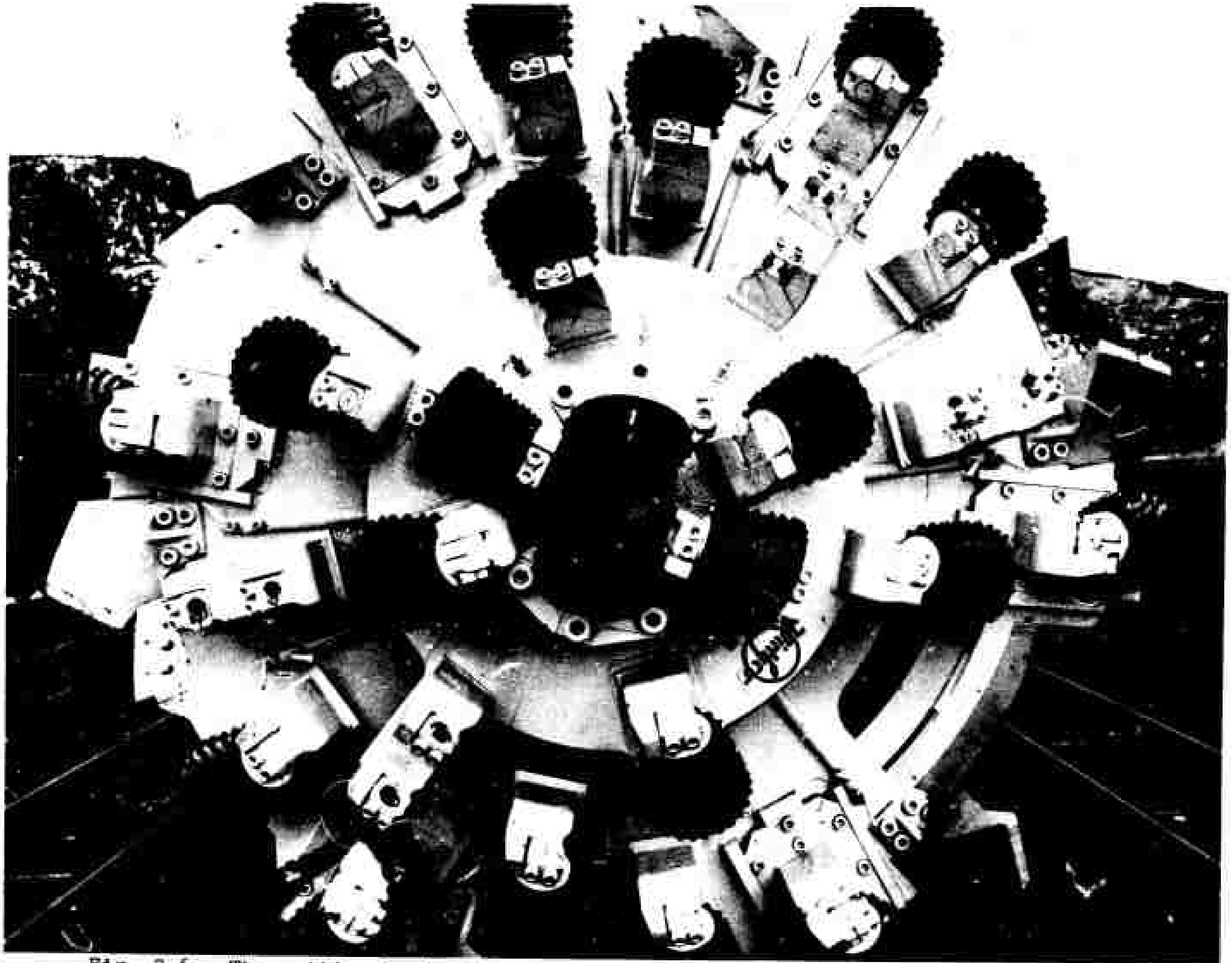

Fig. 2.6. The cutting head used in the Nast tunnel to the end of 1971.

necessarily the fault of the cutters, since some other difficulties were present at the same time.

The head was changed at the end of 1971 from a conical head to a flat face head. This is thought to cause less bending in the head and the cutter saddles and it is hoped in this way to eliminate some of the repairs.

A portion of the finished tunnel is shown in Fig. 2.7. The data collected from the Nast tunnel by the U.S.B.R. for each shift was provided to us for our use. It covers the tunnel bored from November 1970 to January 1972. The length of the tunnel was about 5,500 ft at the end of the period under consideration in this work.

2.3.2 Lawrence Tunnel

Data was received from the Chicago sewer tunnel bored using the Lawrence machine. The tunnel has the diameter of 13'8" and the final length of 12,451 ft. Our data is from one month, July 1971, and corresponds to the advancement of 1,150 ft.

The machine employs disk type cutters. The total number of cutters on the head is 27.

The received logs included time and advancement, thrust (psi), and the hydraulic pressure used to rotate the head. From this information, boring rate and specific energy could be calculated by knowing the relationship between rotary hydraulic pressure and the rotary power.

2.3.3 Calculation of Field Specific Energy

Hustrulid and Ross (3,1) have earlier derived the theory for the calculation of specific energy and cutting coefficient from the

Fig. 2.7. A finished portion of the Nast tunnel (photo courtesy of the U.S.B.R.).

field data. A summary of the theory is presented below.

The total input power to the rock can be given with the expression

$$P = 2\pi nt + T \times B_r' \tag{2.1}$$

where

P = power (ft-lbs/min)

n = RPM, rotation speed of the head

t = torque (ft-lbs)

T = thrust (lbs)

B_r' = boring rate (ft/min)

The rate of rock volume removal is

$$V_T = \frac{\pi}{4} D^2 B_r' \tag{2.2}$$

where

V_T = volume/time (ft^3/min)

D = tunnel bore diameter (ft)

The energy/volume or specific energy is the total input to the rock divided by the volume of the removed rock.

$$E_V' = \frac{P}{V_T} = \frac{2\pi nt + T B_r'}{\frac{\pi}{4} D^2 \times B_r'} \tag{2.3}$$

In this expression E_V' has the units ft-lbs/ft^3.

The boring rate and the specific energy are normally given in ft/hr and the specific energy in in.-lbs/in.^{3}, respectively. The expression 2.3 can be modified to the following form

$$E_V = \frac{2\pi nt + T \frac{B_r}{60}}{0.6\pi D^2 B_r} \tag{2.4}$$

where

E_V = specific energy (in.-lbs/in.^{3})

B_r = boring rate (ft/hr)

Because the rotary power term ($2\pi nt$) is usually much larger than that due to the thrust ($TB_r/60$), E_V can be approximated by

$$E_V = \frac{2\pi nt}{0.6\pi D^2 B_r} \qquad (2.5)$$

In many cases the rotary power is given in terms of horsepower and E_V can be expressed by

$$E_V = \frac{55{,}000 \text{ hp}}{\pi D^2 B_r}. \qquad (2.6)$$

2.3.4 Calculation of Field Cutting Coefficient

There is evidence (4) that in the cutting of rock, the relationship between the cutting (t_i) and normal (N_i) forces can be given

$$t_i = \mu N_i \qquad (2.7)$$

where

t_i = tangential (cutting) force of each cutter

N_i = thrust force per cutter

μ = coefficient of cutting friction.

Assuming that the cutter head is rigid, then the thrust force is the same for all cutters

N_i = N (Constant).

We then have

T = nN

where

T = total thrust

n = number of cutters.

The tangential force (t_n) can be expressed from equation (2.7)

$$t_i = \mu \frac{T}{n} . \tag{2.8}$$

The total applied cutting head torque then becomes

$$t = \mu \frac{T}{n} \sum_{i=1}^{n} r_i \tag{2.9}$$

where

t = total torque

r_i = radius arm of each cutter.

Assuming that the n cutters are evenly distributed,

$$\frac{1}{n} \sum_{i=1}^{n} r_i = \frac{R}{2}$$

where

R = radius of tunnel bore.

The expression for the total torque becomes

$$t = \mu T \frac{R}{2} \tag{2.10}$$

and cutting coefficient (μ) becomes

$$\mu = \frac{2}{R} \frac{t}{T} \tag{2.11}$$

3. DISCUSSION OF RESULTS

3.1 Laboratory Cutting

The summary of the results of the laboratory samples, which represented different types of rock, are given in Table 3.1. Sometimes the first pass did not break material enough so that volume measurements could be made. In these cases the figures given for the second pass represent the first and second passes together. The energy used in the first pass varied between 12% and 17% of the combined energy of the first and second passes.

The results in figures 3.1-3.6 are given as a function of the calculated penetration. Calculated penetration is considered to be the most relevant measure in the laboratory to the boring rate in the field.

Each point in the figures represents one sample. In Fig. 3.6 where four samples are chosen for a more detailed representation, each point represents one pass on the sample.

3.1.1 Specific Energy

Fig. 3.1 shows that there exists an inverse relationship between calculated penetration and specific energy when cutting in different rock types. The inverse relationship does not necessarily represent the relationship in an individual sample. On the contrary, there is some slight evidence of an opposite relationship. This is not, however, well established in these experiments and can be partly the result of the bottom conditions of the cuts.

The cutting method used (cutter, constant indexing) in most cases limits the sizes of the particles produced. Some evidence of this may be found in the size distribution of the cuttings (Table 3.2), where only the Lawrence #1 sample clearly exhibits coarser cuttings than the others. The first pass usually gives coarser cuttings than the later passes, which is due to the unfractured material under the cutter. On each sample, the material right under the edge of the cutter was pulverized and packed. The cutting method may thus effectively limit the value of specific energy obtained.

The average results of the different samples are the most representative for comparing with field boring in different types of rock. It is worth noting that the indexing was kept constant and no attempt was made to find the optimum indexing-penetration ratio for different samples.

3.1.2 Cutting Coefficient

The cutting coefficient shows a direct relationship with calculated penetration (Fig. 3.2). This means that the deeper the cut, the greater is the cutting coefficient. The individual samples do not, in this case, differ remarkably from the trend of the average values of different samples.

In our tests we could increase the forces only by setting a deeper penetration in the cutting machine. The results show that increasing the penetration affects the horizontal force relatively more than the vertical force.

Table 3.1. Linear Cutter Testing Data.

Pass	Average Horiz. Force (lbs)	Average Vertical Force (lbs)	Cutting Coefficient	Penetration Set (in x 10^{-3})	Penetration Calculated (in x 10^{-3})	Specific Energy ($\frac{\text{in-lbs}}{\text{in}^3}$)
			Nast #2			
1	35	2430	.014	30		
2	236	3420	.070	30	42	21700
3	119	2510	.048	30	21	18700
4	202	3220	.063	40	38	17900
5	176	2710	.065	40	42	13800
			Lawrence #1			
1	111	3050	.037	40	46	8100
2	127	2110	.060	60	52	8100
3	233	3070	.076	70	75	10400
4	245	3840	.064	70	83	9900
			Climax #1			
1	26	2290	.011	30		
2	197	3310	.060	30	53	14100
3	78	1370	.057	30	35	7500
4	162	2300	.069	50	53	10200
5	118	1710	.068	40	37	10500
6	137	2000	.068	40	41	10900
			Climax #2			
1	40	2970	.014	35		
2	256	3870	.068	30	59	16800
3	131	2310	.057	40	42	10200
4	196	2800	.070	50	41	16000
5	204	3050	.067	50	52	13000
			Climax #7			
1	80	1160	.070	40	70	3800
2	42	566	.074	60	37	3800
3	120	1370	.088	90	108	3700
4*	168	1870	.092	120	65	5200
*indexing .60 in.						
			Climax #13			
1	76	1100	.072	50	65	3900
2	57	794	.073	60	35	5400
3	120	1340	.090	70	77	5200
4	141	1470	.097	90	108	4400

Table 3.1. (Continued)

Pass	Average Horiz. Force (lbs)	Average Vertical Force (lbs)	Cutting Coefficient	Penetration Set (in x 10^{-3})	Penetration Calculated (in x 10^{-3})	Specific Energy ($\frac{\text{in-lbs}}{\text{in}^3}$)
			Climax #15			
1	116	2260	.052	50	41	9400
2	185	2110	.088	60	72	8600
3	148	1750	.084	70	82	6000
4	201	2140	.094	90	103	6500
5	249	2630	.095	110	81	10200
			Climax #18			
1	33	2470	.014	35		
2	162	4140	.042	30	53	12400
3	137	2130	.065	30	29	15800
4	120	2250	.053	30	28	14000
5	133	2220	.060	30	29	15000

Table 3.2. Particle Size Distribution of the Cuttings (%).

Nast #2

	P 1+2	P 3	P 4	P 5
+14	44.9	45.7	45.1	45.0
-14++150	37.6	37.2	38.9	40.1
-150	17.5	17.1	15.9	14.9

Lawrence #1

	P 1	P 2	P 3	P 4
+14	85.1	69.4	69.0	64.7
-14++150	10.7	21.2	20.8	24.9
-150	4.1	9.4	10.2	10.5

CX #2

	P 1+2	P 3	P 4	P 5
+14	53.3	48.1	46.6	39.2
-14++150	33.6	37.7	38.7	43.5
-150	13.1	14.1	14.8	17.3

CX #7

	P 1	P 2	P 3	P 4
+14	64.7	51.1	49.3	53.6
-14++150	27.5	36.6	37.4	34.8
-150	7.8	12.3	13.3	11.5

CX #15

	P 1	P 2	P 3	P 4	P 5
+14	73.0	45.3	48.4	48.5	40.6
-14++150	22.6	34.4	41.6	41.7	47.7
-150	4.3	9.4	10.1	9.9	11.8

CX #18

	P 1+2	P 3	P 4	P 5
+14	70.4	59.3	56.6	53.6
-14++150	19.5	26.5	28.7	29.1
-150	10.0	14.1	14.8	17.4

CX #1

	P 1+2	P 3	P 4	P 5	P 6
+14	67.3	57.8	59.1	57.3	57.1
-14++150	26.9	35.2	34.2	35.2	36.7
-150	5.9	7.0	6.8	7.6	6.2

CX #13

	P 1	P 2	P 3	P 4
+14	66.3	49.0	54.7	53.2
-14++150	26.9	38.3	34.1	35.8
-150	6.9	12.8	11.2	11.0

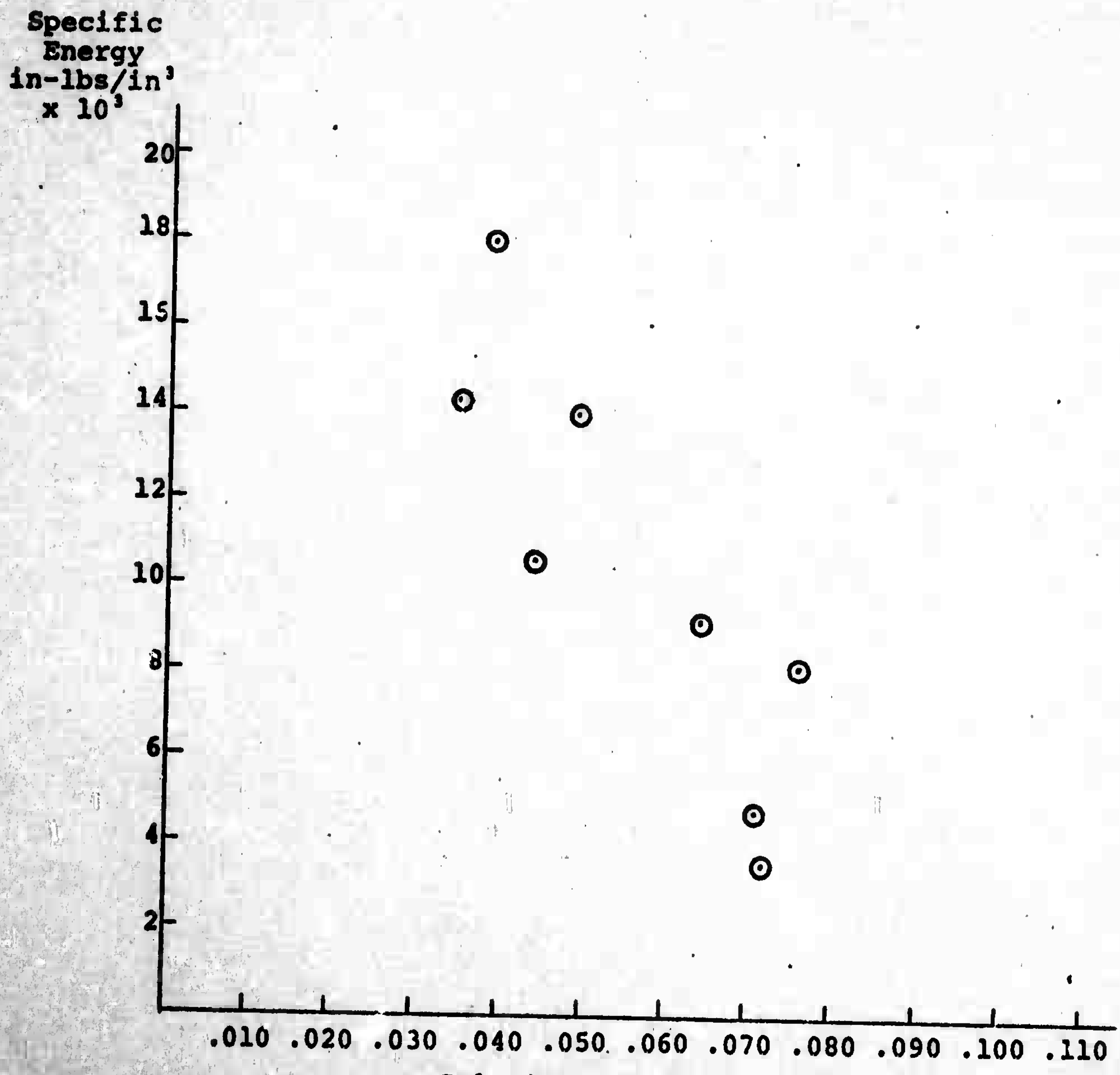

Fig. 3.1. Relationship between specific energy and penetration for laboratory samples.

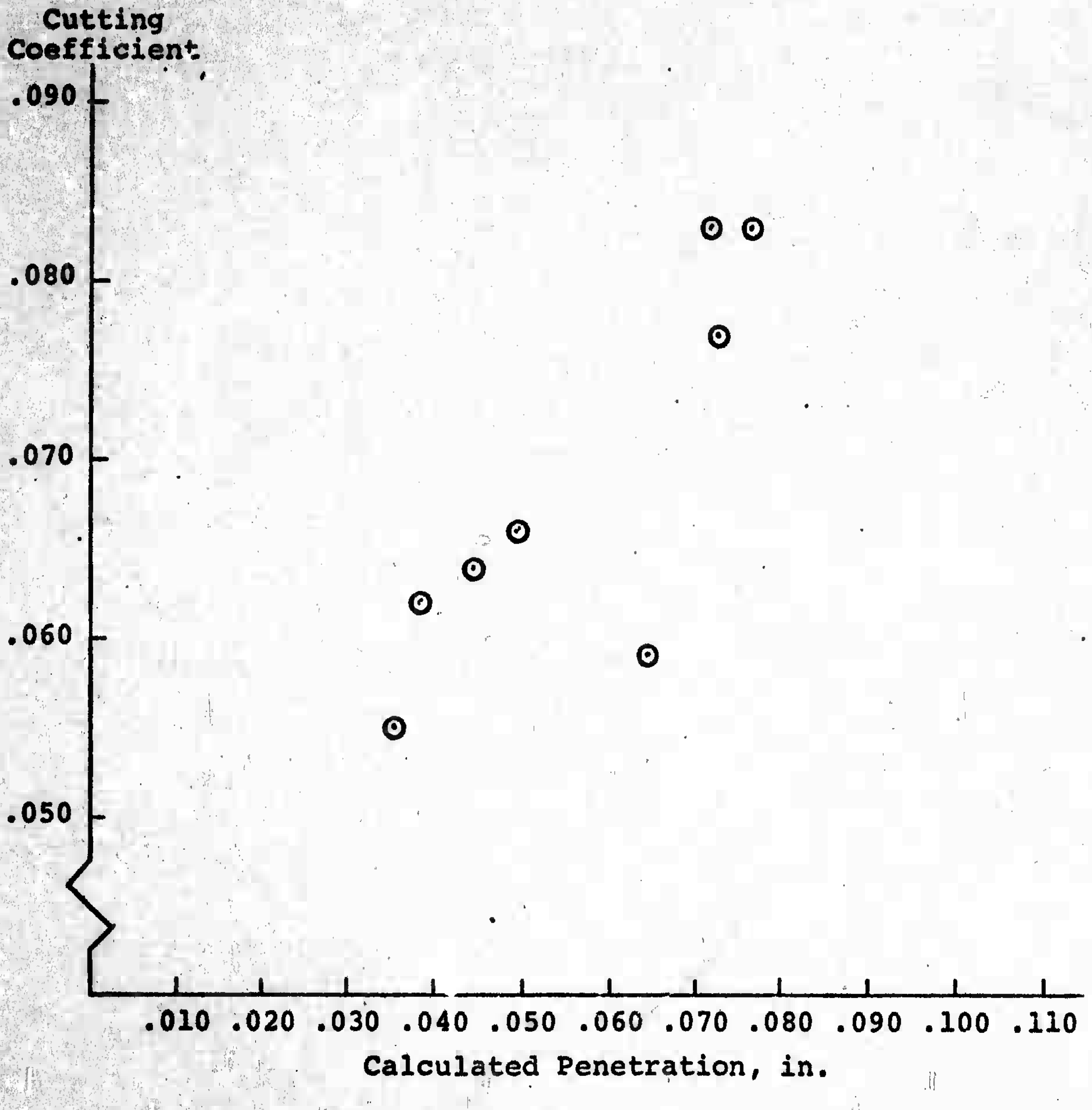

Fig. 3.2. Relationship between cutting coefficient and penetration for laboratory samples.

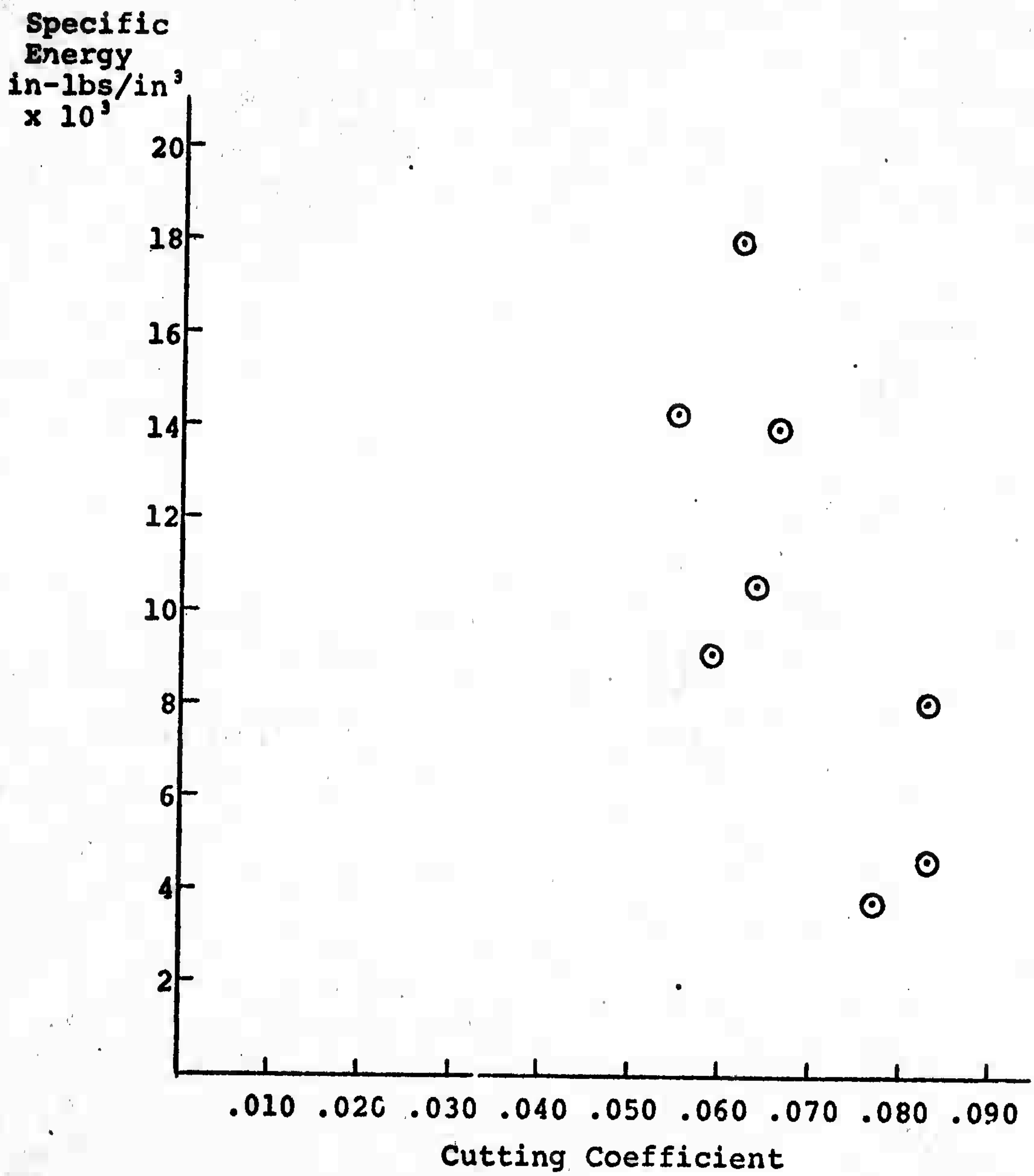

Fig. 3.3. Relationship between specific energy and cutting coefficient for laboratory samples.

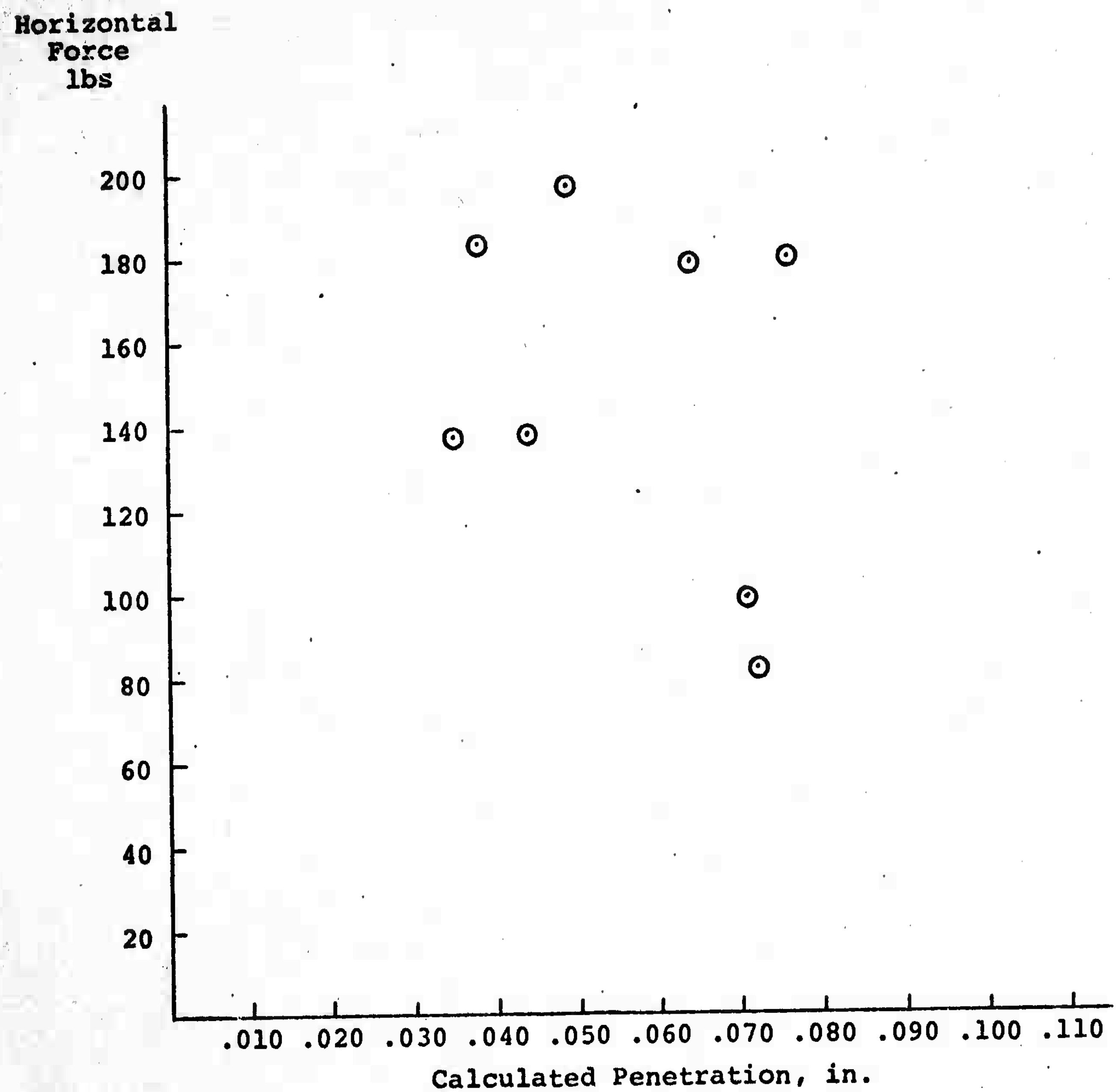

Fig. 3.4. Relationship between horizontal force and penetration for laboratory samples.

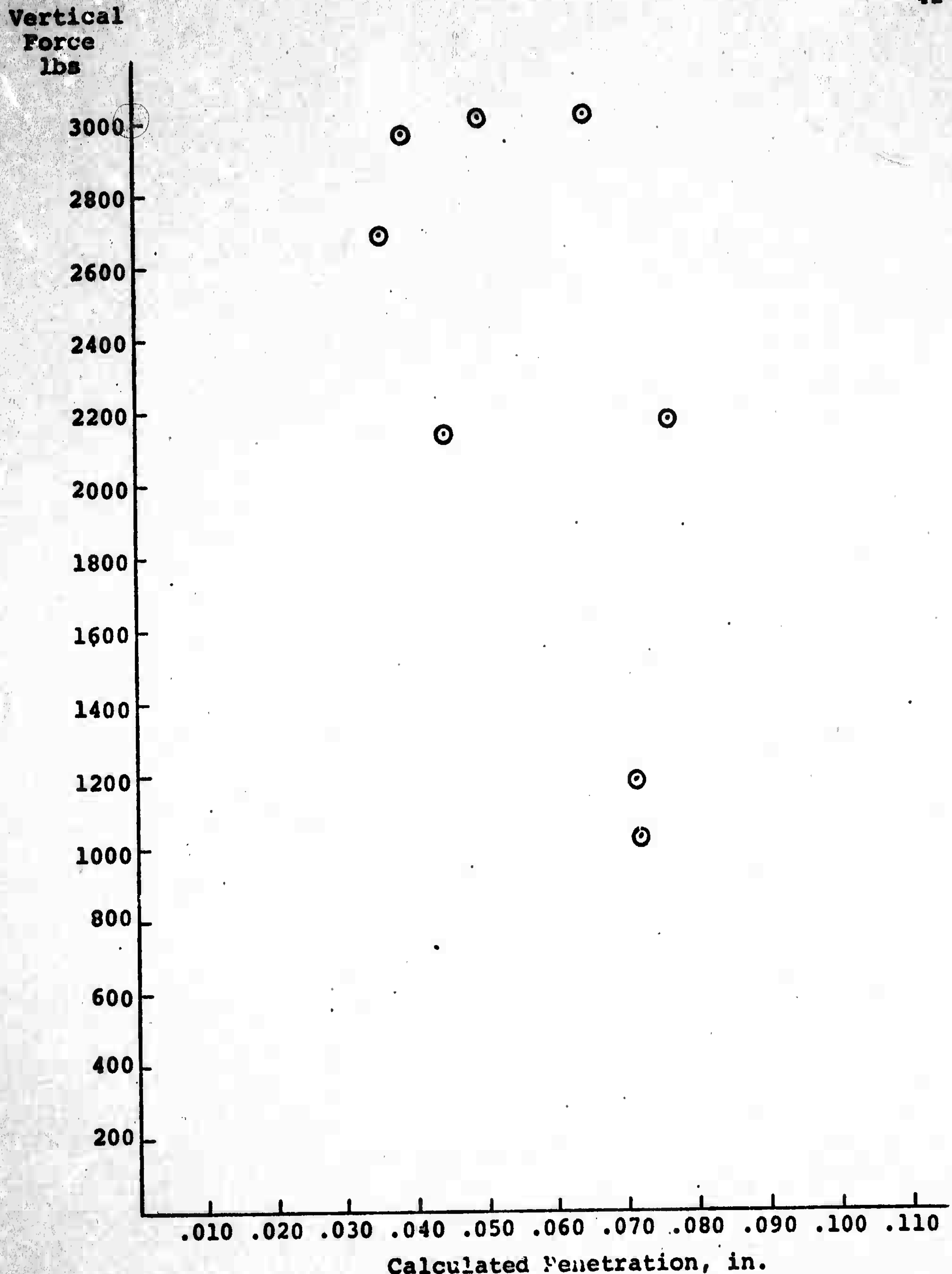

Fig. 3.5. Relationship between vertical force and penetration for laboratory samples.

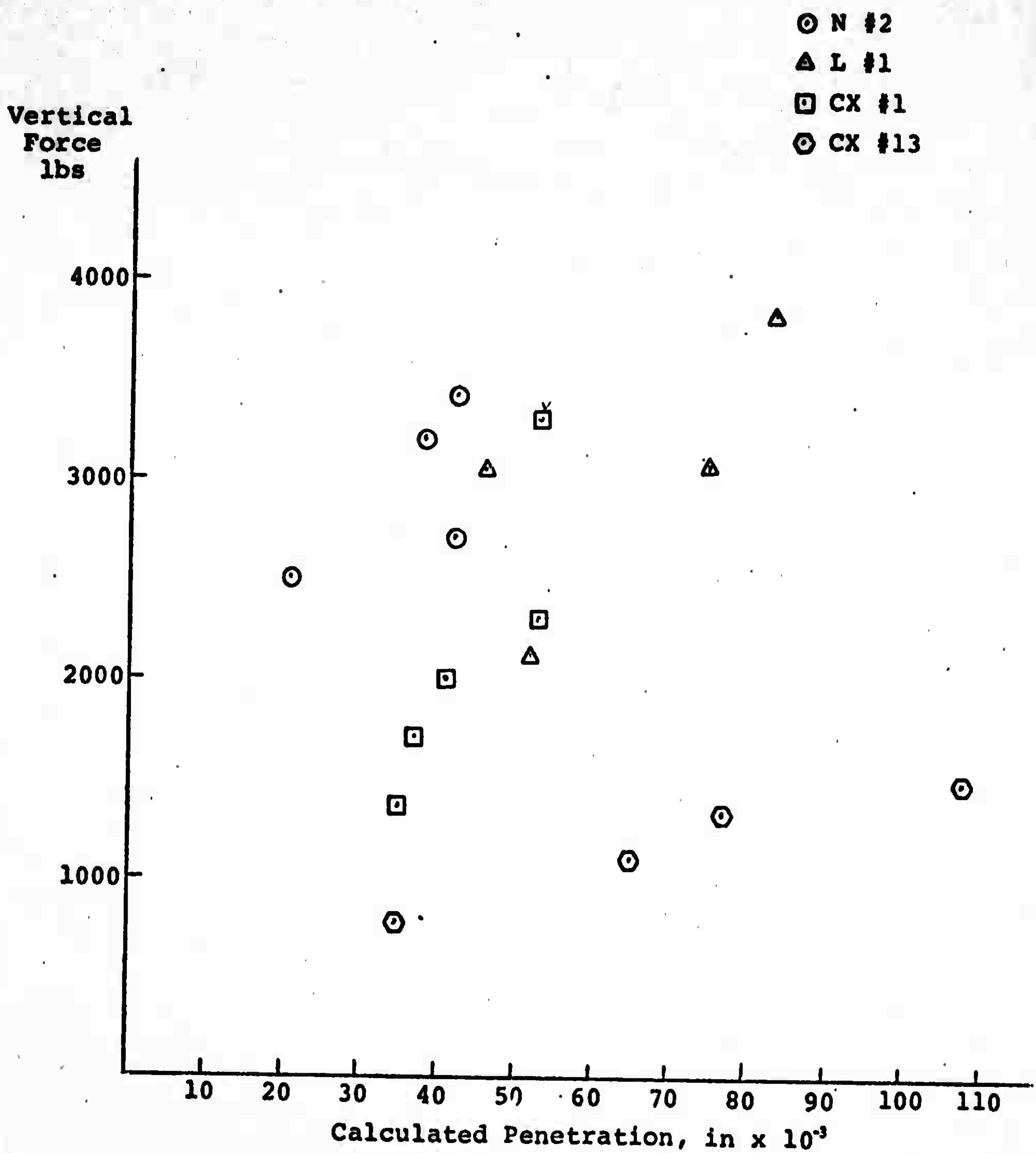

Fig. 3.6. Relationship between vertical force and penetration for the different passes on some laboratory samples.

3.1.3 Specific Energy - Cutting Coefficient

The representation of specific energy as a function of cutting coefficient (Fig. 3.3) shows, as expected, an inverse relationship. This inverse relationship may not represent the situation in one sample. This exception from the average behavior of different samples is due to the same possible reasons mentioned in the discussion of the specific energy earlier.

3.1.4 Horizontal Force

The horizontal force (Fig. 3.4) does not show any clear general relationship with the penetration. In no case the horizontal force alone is any good measure for penetration of the cutter in a rock. On the other hand, horizontal force has quite a dominating role in the cutting coefficient

and the cutting coefficient was shown to have clear inverse relationship with penetration.

The horizontal force increases relatively more with the depth of cut than the vertical force. The Japanese (11, 12, 13) have reported the same type of relationship for cuts in which no interaction occurred between the cuts.

3.1.5 Vertical Forces

The vertical force shows some inverse relationship with calculated penetration (Fig. 3.5). This inverse relationship occurs with the average values of different samples. What this actually tells us is that in the rocks which are easier to cut we get a certain penetration with a lower vertical force than in a rock which is hard to cut.

Earlier work (8,9,10) has shown that the vertical force and penetration should have a direct linear relationship. If we plot the values obtained for different passes on one sample, we get a relationship between vertical force and penetration, which is more or less direct for one sample (Fig. 3.6). The rise for harder rocks is steeper than for softer rocks. Let us note again that no bottoming occurred with our kerf type cutter.

3.1.6 Power Frequency Analysis

To date, little use has been made of the linear cutter records other than to use the horizontal force to calculate the work done in cutting. However, the cutter in its traverse of the surface has encountered each of the hard and soft zones in the rock and the structural defects that may aid in the rock removal process. The degree of chipping taking place is revealed by the variations in the force records. These variations can be quantitatively described by plotting frequency histograms of (1) the interval between successive crossing of the average force level by the actual force record and (2) the distance of the force peak from the average force level. The first histogram should show the presence of a regular set of weakness planes such as might be found in a bedded rock. The size of the potential chips might be inferred from this graph. The second histogram would reveal the tendency for the rock to chip under the particular cutter. A very small variation would indicate a basic crushing failure mode (this has been observed in laboratory tests on Yule marble), whereas a large variation would suggest chipping as a principal mode. The variation would also suggest the degree to which a particular cutter type might be applicable, for example, in material showing very large, closely spaced force variations. The cutter chatter would result in carbide chipping rather than a more even abrasive wear.

The linear cutting force records for the Nast and Lawrence samples were analyzed in this regard and the resulting frequency-interval between successive crossing histograms are given in Figures 3.1.6a and 3.1.6b, respectively. Each of the histograms has been made using the records from at least six cuts. Although histograms made using both the horizontal and vertical force records are given, since the shapes are very similar, in the future it may be possible to calculate only one.

The results show that for both rock types the interval between successive peaks is generally small, the material being removed in small chips. However, in the histogram for the Lawrence sample a large peak occurs at an interval of about 0.65 inches. This would suggest the presence of a weakness that might be exploited. Such a clear peak is not present in the Nast results. The difference in size distributions of the cuttings would also suggest that such weaknesses are present in the Lawrence sample and absent in the Nast. Furthermore, extensive work on this method of analysis is being carried out and this approach looks promising.

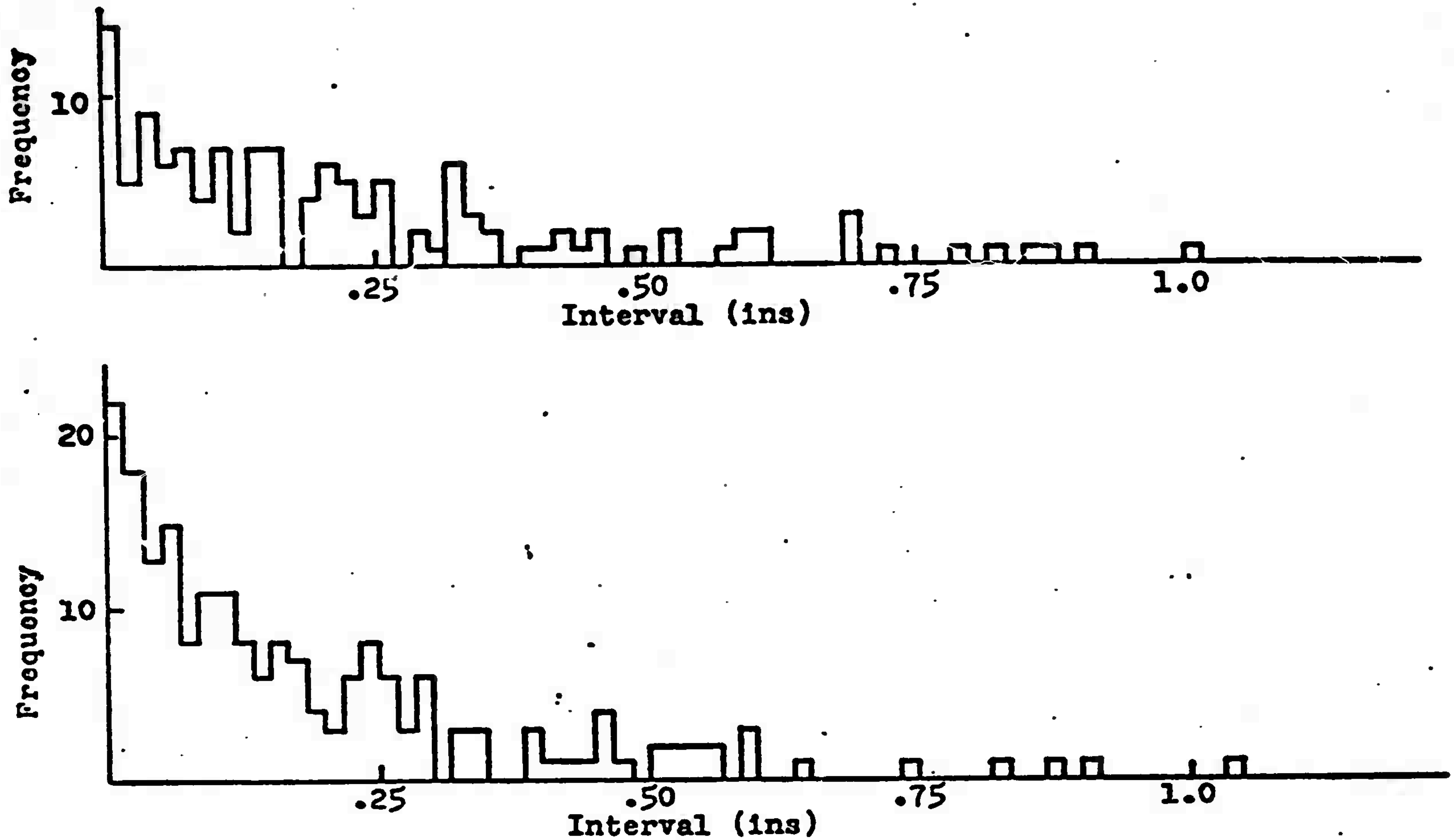

Fig. 3.1.6a Frequency analysis of the linear cutting records. Nast sample 2, Pass 3.

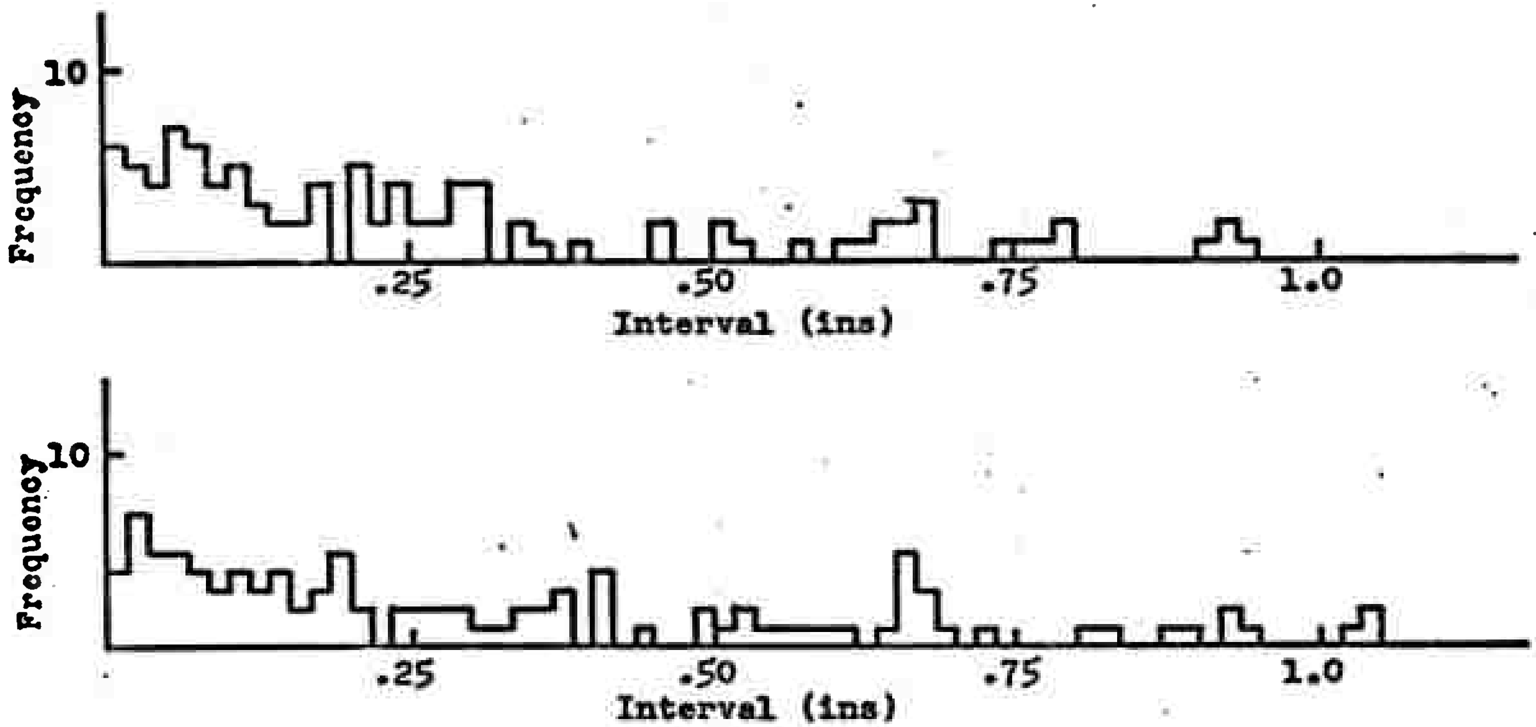

Fig. 3.1.6b Frequency analysis of the linear cutting records. Lawrence Sample 1, Pass 3.

3.2 Laboratory Cutting Results Calculated by the Hybrid Computer

Cutting records of laboratory samples were recorded on magnetic tape using a Honeywell 8100 tape recorder. This tape was in turn played into a hybrid computer and values of cutting coefficient and work were determined for each cut.

Definite and characteristic cutting records were obtained from samples of different locations. The Nast samples showed variations in cutting coefficient typical of hard rocks where chipping occurs. The Lawrence samples being of fine-grained, homogeneous, hard, and brittle rock displayed a characteristic tendency for larger chips. The effect of cracks, soft and hard spots, and weakness planes was quite evident in the cutting records and energy values for significant portions of the cuts, further indicating the advantage of exploiting the natural weaknesses. Overbreak from previous passes also caused noticeable variations in the force records and cutting coefficient.

The cutting coefficient does not necessarily indicate what kind of rock we are cutting. However, the energy curve does indicate the quality of rock being cut, i.e., if it is easy or hard to cut. Often easy and hard cutting portions occurred on the same sample. This is especially true of the

Climax samples, where the rock bored is highly variable, making correlation and prediction very difficult.

It was found that the horizontal force was much more sensitive to rock variations along the cut than the vertical force and the cutting coefficient is most sensitive to changes in horizontal force. Using the cutting coefficient record and the energy curve, a reasonable description of the boreability of the sample can be offered.

3.3 Tunnel Boring Results

3.3.1 Nast Tunnel

Boring rate, thrust, torque, cutting coefficient, and specific energy were calculated for each shift from the data provided from the Nast tunnel.

The rock along the tunnel was classified in the geologic logs as excellent, good, fair, or poor and as qualities between these. The classification is based mainly on the structure of rock, and has consistency, although it is mainly qualitative in nature.

The calculated data was grouped according to the rock qualities in seven different groups. The results are given in Table 3.3 and Figs. 3.7 - 3.11. Rock quality grouping gives perhaps the best idea about the factors affecting rock boreability in the tunnel.

The general trend is that the boring rate increases when going from excellent to poor rock with exception that between fair and poor rocks. The specific energy decreases with increasing boring rate. The cutting coefficient tends to increase when going from excellent to poor rock; more exceptions than in the boring rate and specific energy occur though. Thrust and torque do not show any clear tendency in the results in Table 3.3, though thrust has been higher in excellent and excellent-good rocks than in the others.

The other quantities are given as a function of boring rate in Figs. 3.7 - 3.10. Figure 3.11 gives the relationship between specific energy and cutting coefficient. We had only one laboratory sample from the Nast tunnel, therefore we have to compare these field boring results to the average behavior of all laboratory samples.

<u>Specific Energy</u>

As expected, the specific energy is observed to vary inversely with the boring rate. Laboratory results with different samples

Table 3.3. Boring Data from Nast Tunnel

Rock Quality	Boring Rate ft/hr	Specific Energy in-lbs/in³	Cutting Coefficient	Thrust lbs x 10³	Torque ft-lbs x 10³
Excellent	2.31	16600	.088	522	112
Excellent Good	2.67	15200	.086	518	109
Good	2.88	12800	.095	461	104
Good Fair	3.06	12300	.092	500	109
Fair	3.66	8600	.105	401	102
Fair Poor	3.22	10200	.100	463	111
Poor	4.21	8800	.112	423	114

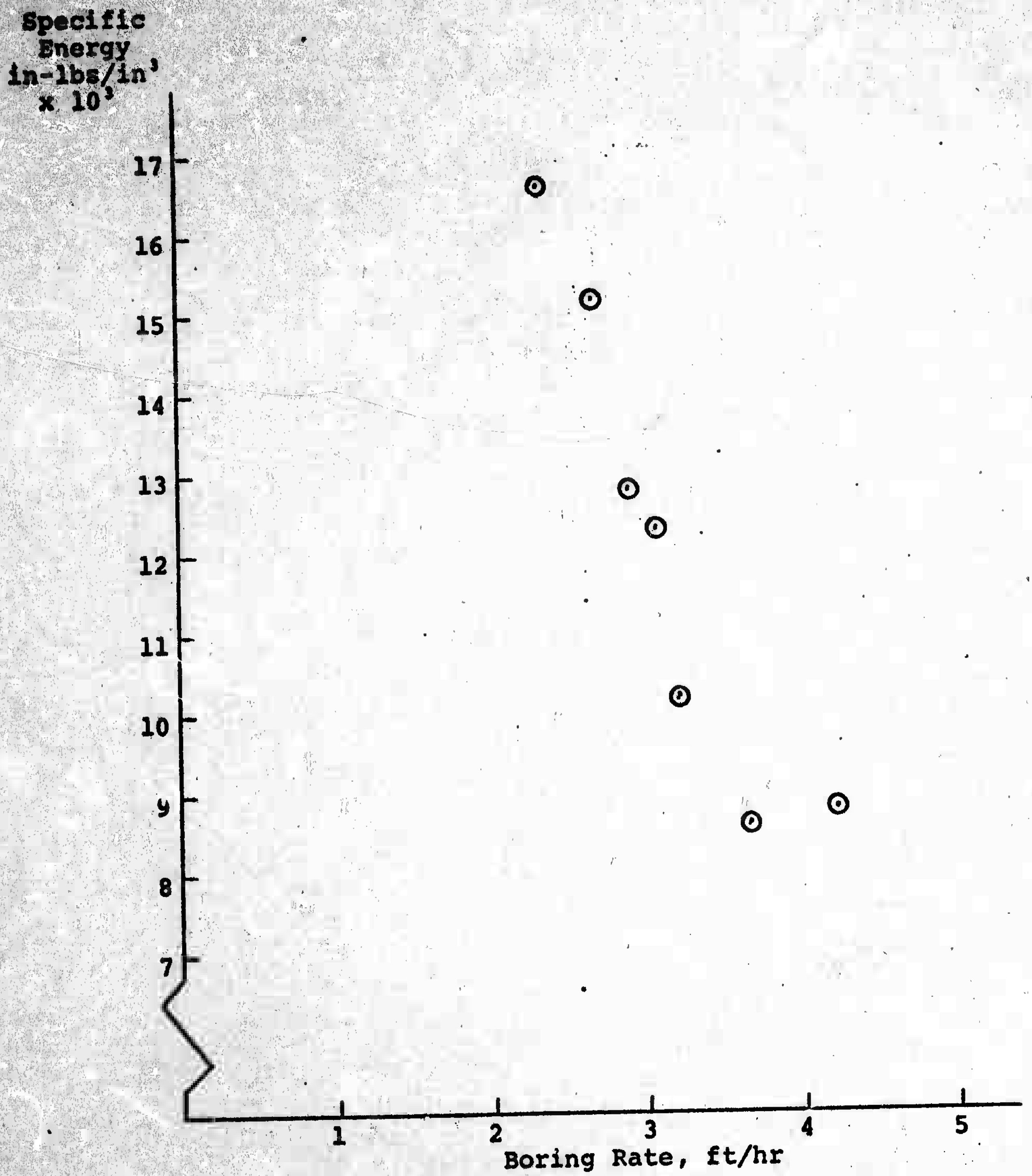

Fig. 3.7. Relationship between specific energy and boring rate for the Nast tunnel data. Points represent the average values of the seven groups of geological classification.

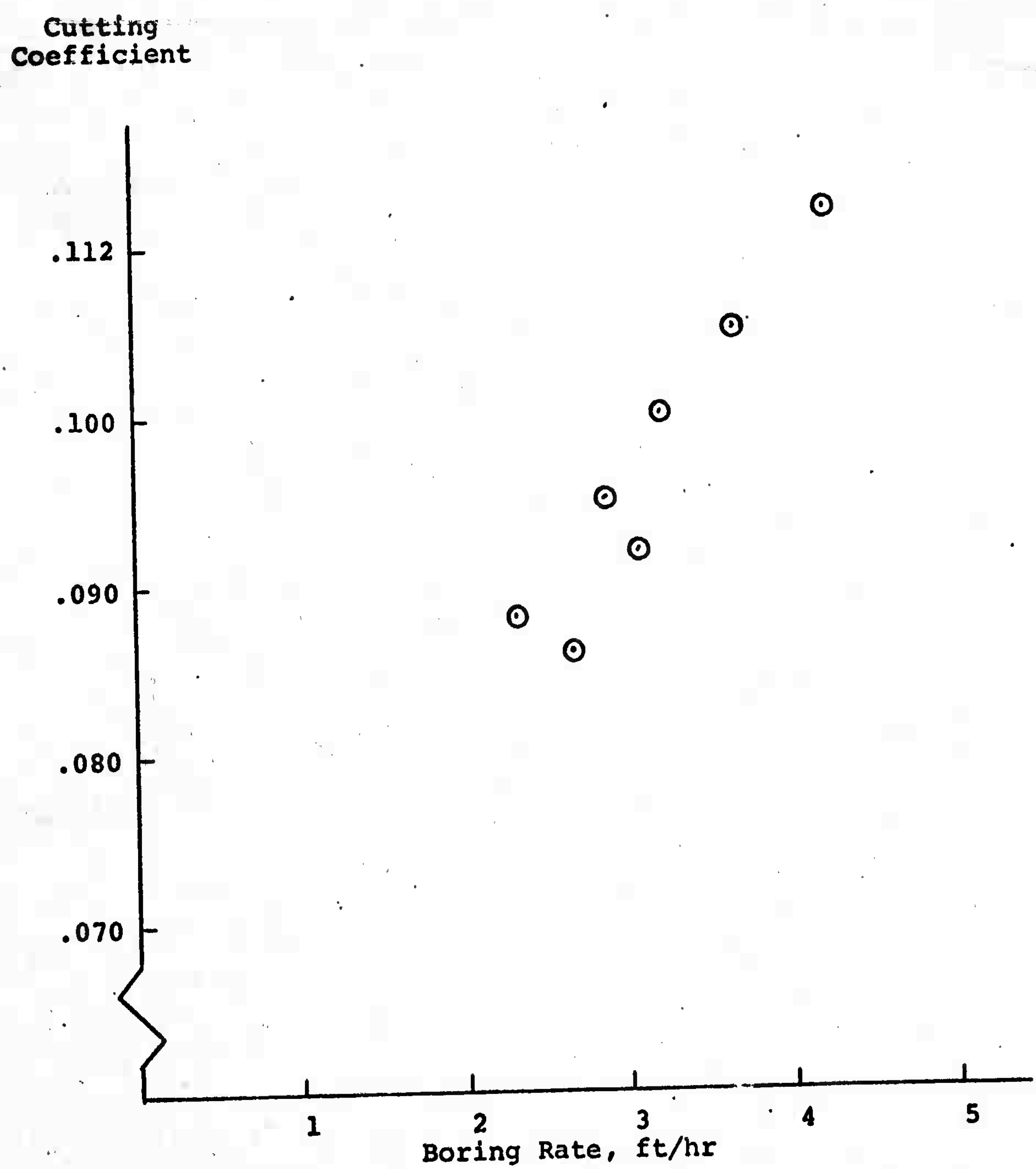

Fig. 3.8. Relationship between cutting coefficient and boring rate for the Nast tunnel data. Points represent the average values of the seven groups of geological classification.

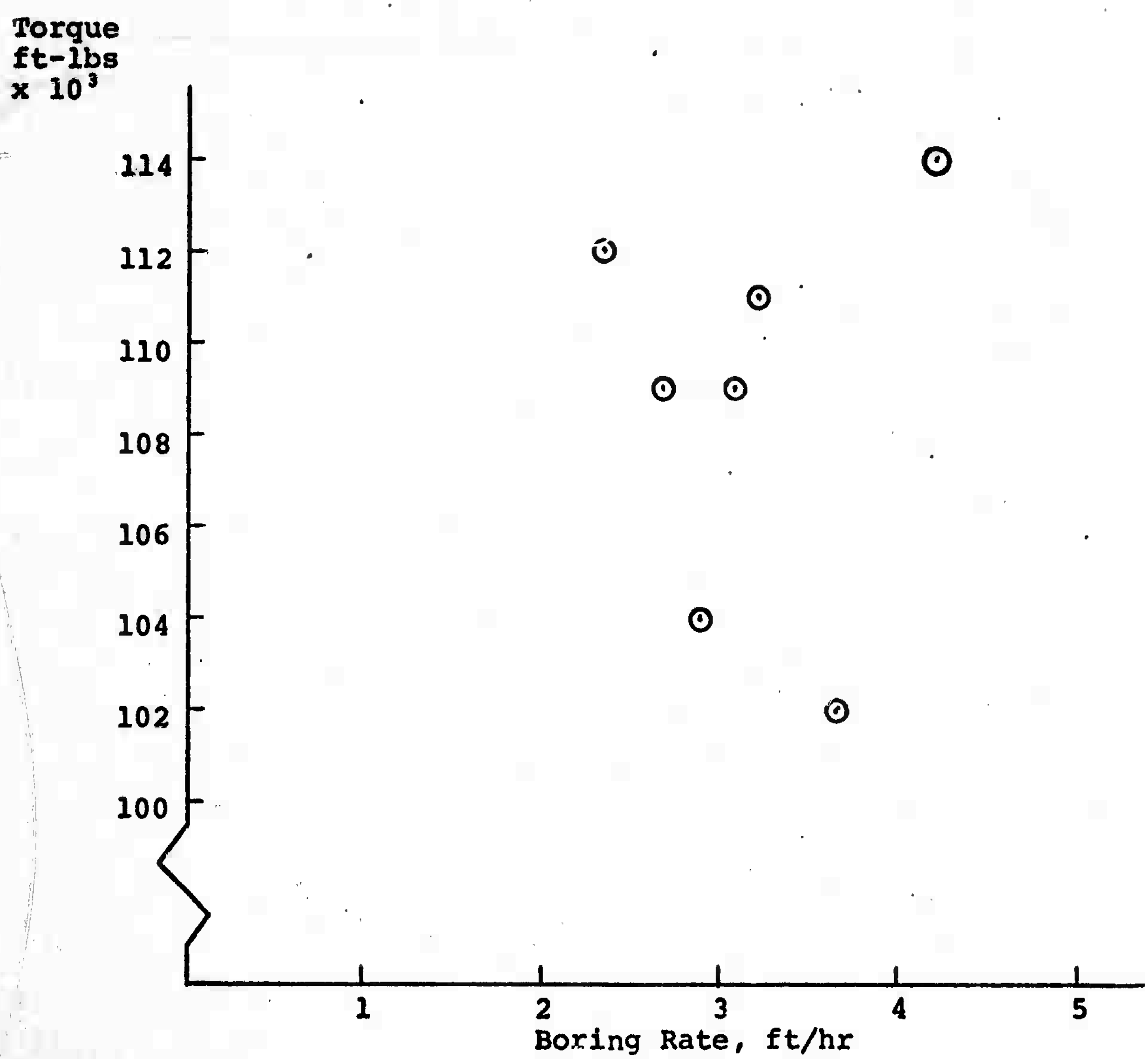

Fig. 3.9. Relationship between torque and boring rate for the Nast tunnel data. Points represent the average values of the seven groups of geological classification.

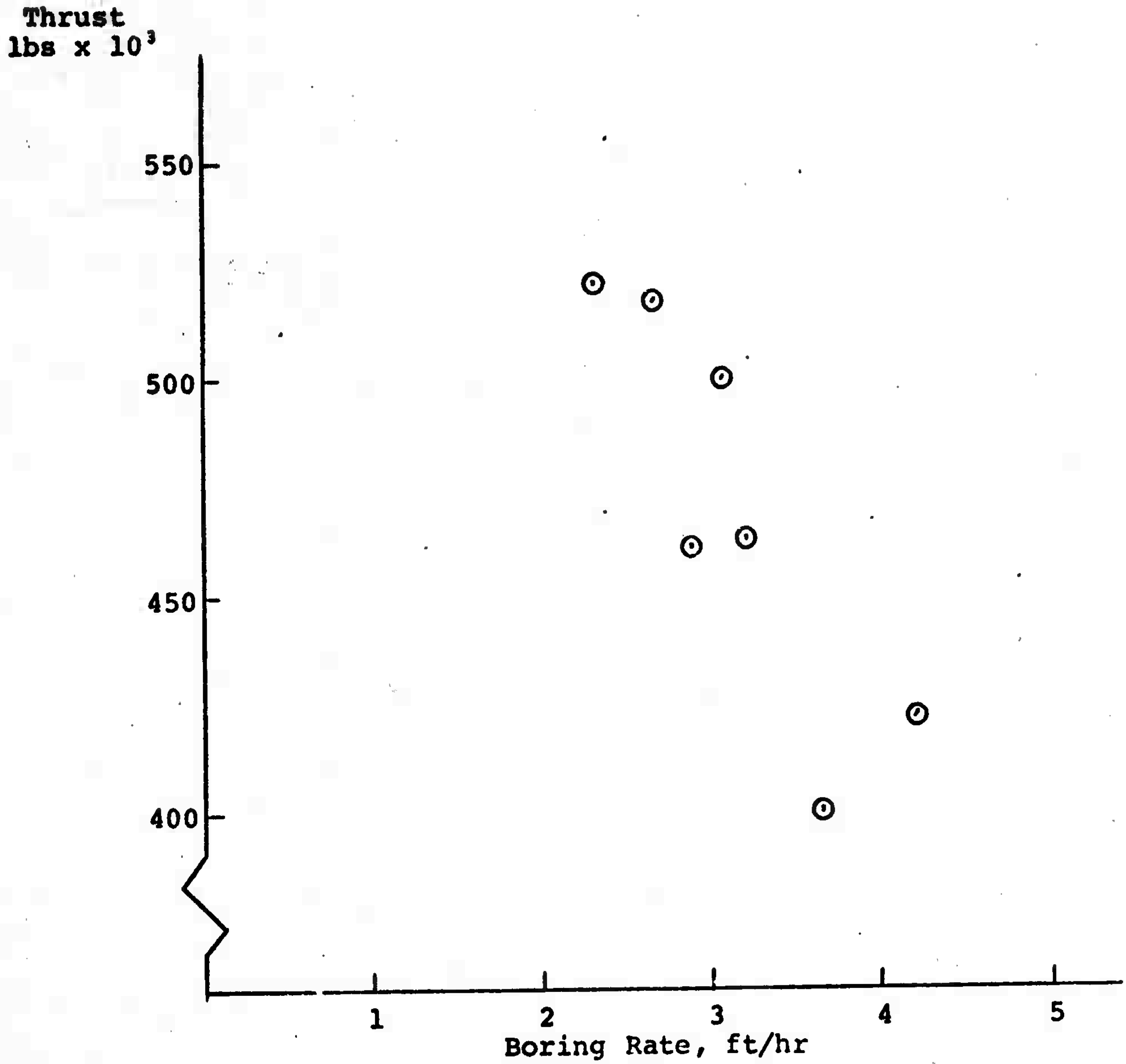

Fig. 3.10. Relationship between thrust and boring rate for the Nast tunnel data. Points represent the average values of the seven groups of geological classification.

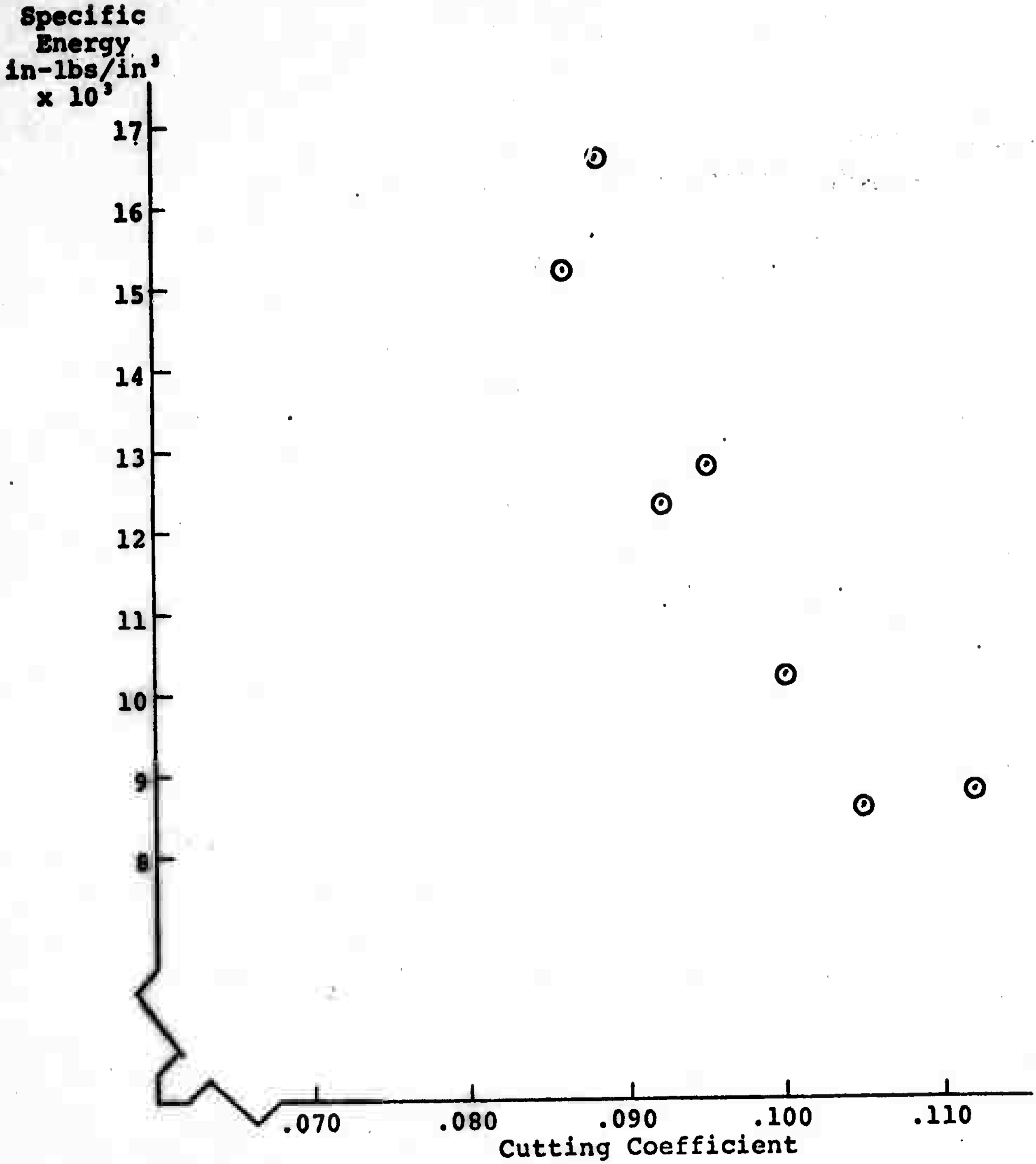

Fig. 3.11. Relationship between specific energy and cutting coefficient for the Nast tunnel data. Points represent the average values of the seven groups of geological classification.

(Fig. 3.1) showed the same type of relationship between specific energy and calculated penetration. In both cases the higher boring rates or deeper penetrations and lower specific energies are obtained in poorer rock. Because the rotation speed of the cutting head varied in the field, boring rate and penetration per revolution are not exactly the same measure. The variations in rotation speed were, however, such that they should not prevent us from comparing field and laboratory results.

The Nast laboratory sample gave the specific energy value of 18,300 in.-lbs/in.^{3}. The sample was taken from the area which is classified as good-fair. The sample was intact and did not include any major structural weaknesses and thus can better be compared with excellent rock quality. When boring in excellent rock, the field specific energy was 16,600 in.-lbs/in.^{3}. As can be expected, the laboratory value is higher probably due to finer cuttings.

Cutting Coefficient

The boring rate has an almost direct linear relationship with the cutting coefficient (Fig. 3.8).

The laboratory results of different samples (Fig. 3.2) also gave direct relationships between the cutting coefficient and penetration. In this respect, the field and laboratory results are consistent. The higher cutting coefficient value means deeper penetration and faster boring.

The Nast laboratory sample gave the average cutting coefficient as 0.062 (the first pass excluded). This is below the lowest field cutting coefficient value which is 0.086 for excellent-good rock.

Specific Energy - Cutting Coefficient

There is an inverse relationship between specific energy and cutting coefficient (Fig. 3.11). This inverse relationship was also observed in laboratory experiments (Fig. 3.3). We cannot compare the results in one sample to the field results with different rocks, since we also had differences in the laboratory results of one sample and of all samples.

3.3.2 Lawrence Tunnel

From data of Lawrence tunnel in Chicago, boring rate and specific energy were calculated. The boring in the Lawrence tunnel has been very consistent and "homogeneous" compared to the boring in the Nast tunnel. The achieved boring rates are twice that achieved in the Nast tunnel and specific energies remarkably lower.

We had one laboratory sample from the Lawrence tunnel.

Specific Energy

Specific energy was calculated from the rotation horsepowers. The points in Figs. 3.10 and 3.13 represent the weighted averages of each one hundred feet.

Specific energy and boring rate (Fig. 3.12) have an inverse relationship which is almost linear. The inverse relationship was also found in the results of the Nast tunnel.

The average specific energy value of the Lawrence tunnel laboratory sample was 9100 in.-lbs/in.^{3}. This is much higher than the specific energy values obtained in the field boring. An

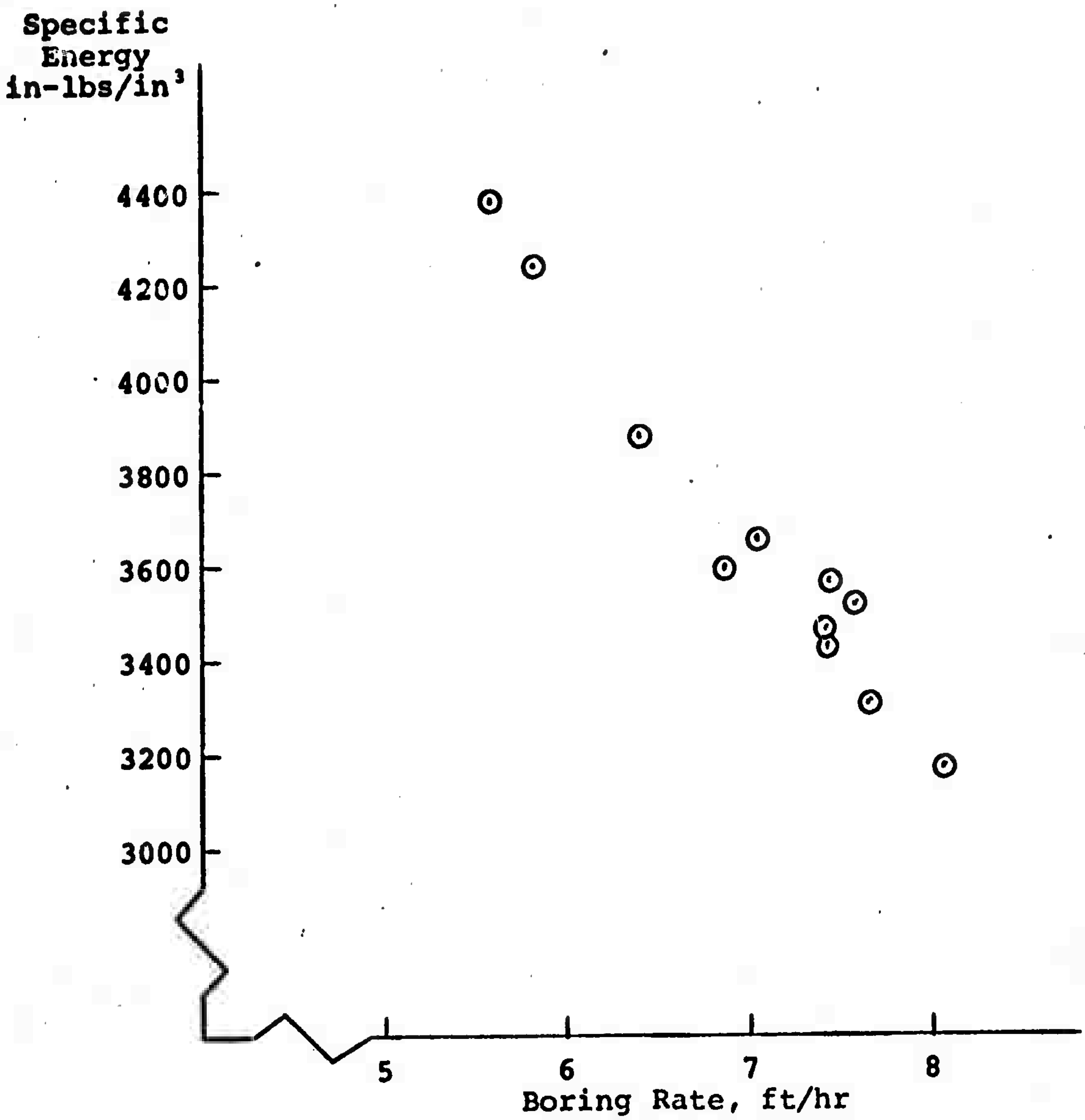

Fig. 3.12. Relationship between specific energy and boring rate for the Lawrence tunnel data. Points represent the average values of each one hundred feet.

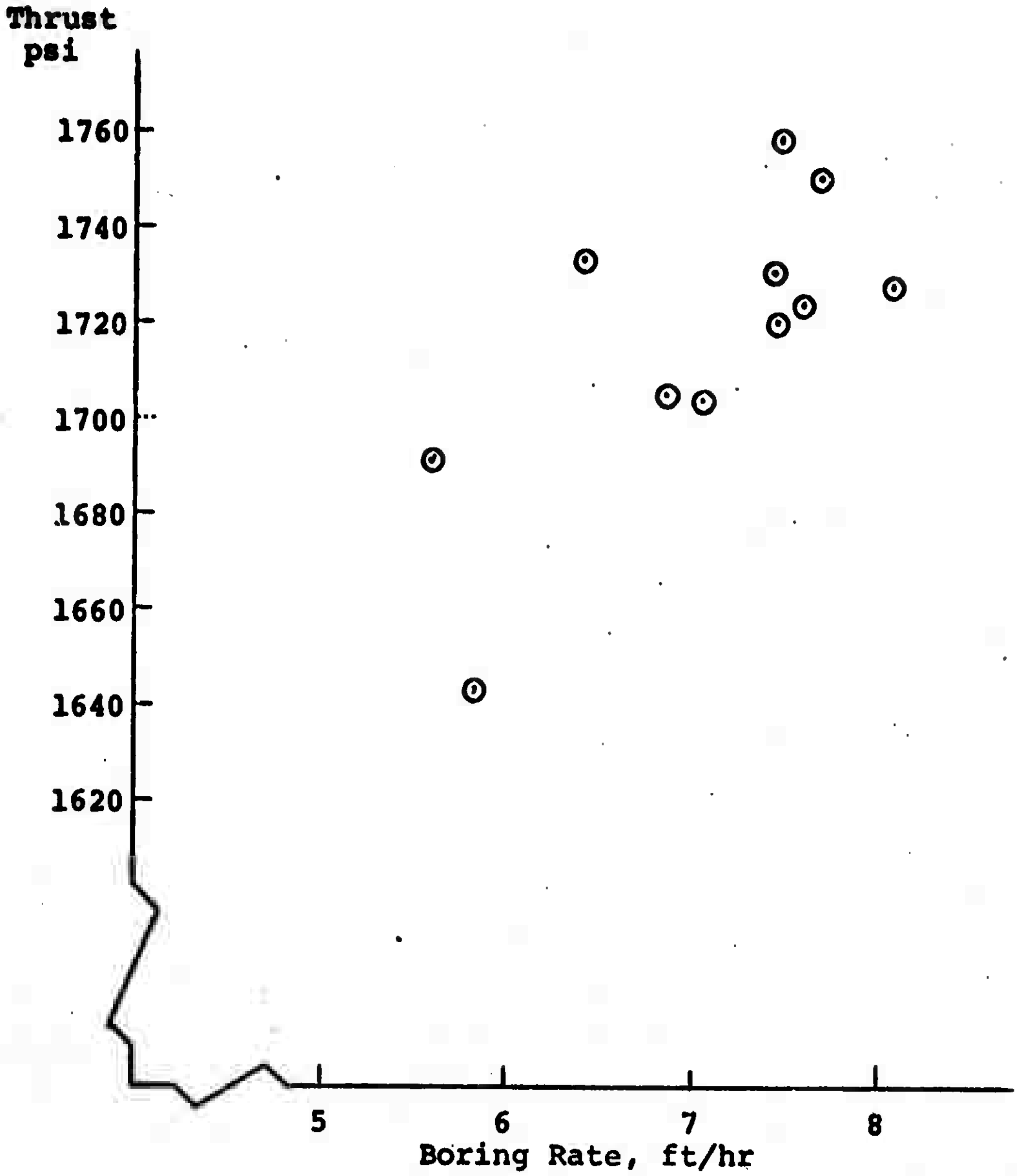

Fig. 3.13. Relationship between thrust and boring rate for the Lawrence tunnel data. Points represent the average values of each one hundred feet.

explanation of this large difference may be that very effective chipping occurred in this rock. This causes large differences in the particle sizes of field and laboratory cuttings.

Thrust

The most remarkable difference when Lawrence tunnel data is compared with the results of the Nast tunnel is that thrust has a direct relationship with boring rate in the Lawrence tunnel (Fig. 3.13).

Two factors: (1) disk type cutters have been used in the Lawrence machine and with these cutters bottoming does not occur, and (2) the rock in the tunnel has been rather homogeneous, may be the main reasons for this direct relationship.

The direct relationship was also found in the results of different passes in the laboratory sample (Fig. 3.6). This seems to be the real behavior when rock type is not changed and if the cutter does not cause limitations. If the strength of rock is low, it limits the thrust which can be used.

3.4 Prediction of Boring Rate

Both the field boring data and the laboratory cutting results give an inverse relationship between specific energy and cutting coefficient. This suggests that using the equations (2.5) and (2.10) we could derive boring rate for field boring.

$$E_V = \frac{2\pi nt}{0.6\pi D^2 \times B_r} \quad (2.5)$$

$$t = \mu T \frac{R}{2} = \mu T \frac{D}{4} \quad (2.10)$$

where

E_V = specific energy (in.-lbs/in.^{3})

t = torque (ft-lbs)

n = RPM

D = diameter of bore (ft)

B_r = boring rate (ft/hr)

T = thrust (lbs)

μ = cutting coefficient.

We get from (2.5)

$$t = \frac{0.6\pi D^2 \times B_r \times E_V}{2\pi n} \tag{3.1}$$

Equating (3.1) and (2.10) and arranging the terms we obtain

$$B_r = \frac{nT}{1.2D}\,\frac{\mu}{E_V} \tag{3.2}$$

Thus by knowing cutting coefficient and specific energy we should be able to determine boring rate in various conditions.

The results of this work and also earlier research (1) show that cutting coefficient is very much dependent on the cutter design. In any case we should be able to obtain the limits for cutting coefficient from the design. The Nast tunnel data (Table 3.3) shows that cutting coefficient increases by 27% from excellent to poor rock, but boring rate increases by 82% at the same time.

The specific energy value which is obtained in the laboratory is generally higher than that obtained from field data. Two basic reasons can be pointed out as a reason for this. First, the laboratory sample does not include structural weaknesses of the rock in situ (or only in minor extent). Second, the size of cuttings is smaller than in the field.

In our results for the Nast tunnel the difference between laboratory specific energy and field specific energy for excellent rock type is small. The reason may be that cuttings in the Nast tunnel were fine, especially in excellent rock type. The difference between laboratory and field specific energy values for the Lawrence tunnel is remarkable. This may be due to the great ability of this rock to chip, which causes differences in particle size between laboratory and the field results.

We can obtain the upper limit to specific energy from laboratory cutting, but our value may be much too high depending on the rock. Without particle size analysis or a method with which we can take into account the effect of particle size to specific energy, we can only poorly relate laboratory and field specific energies. Because the structural features are very dominant in the field we should have a means to estimate their influence to the specific energy in boring.

For the time being the main difficulty in using equation (3.2) for boring rate prediction is the uncertainty in specific energy.

The equation (3.2) shows also the direct relationship between boring rate and thrust. This can be seen in the results only if specific energy and cutting coefficient remain constant. This explains the difference between the data of the Nast and Lawrence tunnels (Figs. 3.10 and 3.13).

4. CONCLUSIONS

The most dramatic result of this study was the effect of structural features and rock weaknesses in the cutting of rock. This indicates that machine design should make better use of these weaknesses for more efficient rock removal.

As is expected, the laboratory values of specific energy were higher than field values. Since specific energy is a good indication of the boreability of a particular rock type it is essential to develop the scaling relationships that relate laboratory specific energy values to field values. Certain definite relationships are shown which indicate the need for a better knowledge of the particle size of cuttings and the structure of the rock to be bored.

The inverse relationship between specific energy and cutting coefficient, both in the field and in the laboratory, supports the idea that machine design should try to increase cutting coefficient to obtain better boring results. Present machine design puts a definite limit on the cutting coefficient. Increasing the depth of cut increases the cutting coefficient and also the size of the cuttings. This would result in lower specific energy and reduced cutter wear per volume of rock removed.

The wide variations in loads on the cutter should be investigated both as a dynamic loading to the cutter as it affects cutter life and as a possible indication of the failure characteristics of a particular rock type being cut by a particular cutter type.

PART III

REVIEW OF PERTINENT LITERATURE

1. INTRODUCTION

Although the emphasis during the contract was on construction of the large linear cutting machine and continued testing using the small linear cutting machine, a continuing search of the literature was carried out. Using the work of previous investigators, initial guides for our continuing research were developed. Areas of interest relating to rock boring were investigated such as:

1. Independent cuts with roller and pick cutters.
2. Multiple and dependent parallel cuts with roller and pick cutters.
3. Static bit penetration tests.
4. Dynamic fracturing of rock.
5. Stress distribution and rock behavior under various bits and cutters.
6. Effects of cutter types and penetration of specific energy.
7. Optimum indexing-penetration ratio for various cutter-rock combinations.
8. Effect of boring rate and/or speed of cutting.
9. Effect of rock properties.
10. Scaling relationships.

A number of Japanese papers were translated and their information incorporated into the literature section.

2. SUMMARY OF PERTINENT FINDINGS IN THE LITERATURE

2.1 Independent Cuts With Roller and Pick Cutters

It has been shown (2) that the applied thrust on a cutter affects penetration in two ways; a) by local crushing and compaction of the material directly under the cutter, and b) by transmission into the solid as a stress that is often relieved by fracture formation extending from the bottom of the cut to the surface. Cook (4) defined the location of chip formation by:

$$F_n = kP_n + F_o$$

where:

F_n = thrust necessary to form the n^{th} chip

k = constant relationship between applied thrust and resulting penetration for a sharp wedge

P_n = penetration at the formation of the n^{th} chip

F_o = $F_1 - kP_1$ where F_1 and P_1 are the force and penetration necessary to produce the first chip.

Variations in the slopes of thrust-penetration curves suggest that penetration is dependent upon the applied thrust, the shape of the cutter and the physical properties of the rock (3). It was also found that the wide spacing of teeth on a toothed kerf cutter yielded the greatest amount of debris per cut.

It was found by the Japanese (11) that for straight kerf type cutters, cutting resistance depended on depth of cut, radius of cutter, and rock properties, but the included angle of the cutting edge had little effect. A further study (12) indicated width of groove from a single cut increases linearly with depth of cut.

2.2 Multiple Indexed Cuts

It was found that there exists a critical spacing between successive parallel cuts at which the cuts become independent. As the indexing is increased from zero, specific energy decreases until an optimum value of indexing is reached. Increasing the indexing beyond this optimum will cause an increase in specific energy. The optimum indexing changes with penetration and rock type, but generally the best indexing to penetration ratio is constant around 1.5 to 2.0.

Tests were also performed that indicated specific energy decreased rapidly with increasing cutting coefficient. This again indicates the possible advantage of pick cutters over roller type cutters.

2.3 Static Bit Penetration Tests

Static bit penetration tests were used in describing the fracture mode of various rock types. Different bit types were used and results such as chip size and shape and specific energy were compared to our laboratory cutting results.

2.4 Dynamic Fracturing of Rock

Much work has been done in the dynamic testing of rock. The resulting theories of rock failure have been examined as they relate to rock boring. The occurrence of relatively deep subsurface cracks after impact by a sharp wedge indicates possible future advantage in applying a dynamic load to the cutters or directly ahead of the cutters. This would create artificial weakness planes which, as shown in experimental work, increases the efficiency of rock removal by the cutter.

2.5 Stress Distribution and Rock Behavior Under Cutters

Much information concerning the stress distribution under a cutter and chip formation using various cutters has been collected and is being used in our own study of the problem. A full understanding of the situation around the cutter is incomplete, especially as concerns the effect of rock weaknesses.

2.6 Effect of Cutter Type and Penetration on Specific Energy

A number of tests (3,4,5,8,10,11,12) using different cutter types were performed. Differences are apparent, especially between roller kerf cutters and pick cutters. The roller cutters are limited to cutting coefficients of the order of 0.1 or smaller. In addition, the button insert kerf cutter is subject to bottoming out of the buttons at increased loads. The pick cutters could achieve penetrations up to 2 inches and cutting coefficients of 2.0 or greater. Since specific energy decreases rapidly with increasing cutting coefficient, with an optimum of 1.5 to 2.0, it would appear the pick cutter may be more efficient.

2.7 Optimum Indexing-Penetration Ratio

As mentioned previously there exists an optimum indexing distance for a particular depth of cut. Although the ratio of indexing to penetration is generally best at about 1.5, this varies with cutter type and rock. With the taking of deeper cuts it becomes increasingly important to determine and set the optimum indexing-penetration ratio for a particular boring situation.

2.8 Effect of Boring Rate and/or Speed of Cutting

In addition to variations in rotational speed of different boring machines, the speed that individual cutters traverse the face varies from the center cutters to the outside cutter. Studies have been performed in an effort to determine the effect of rate of cutting on specific energy. One such study (9) suggested that as cutting speed is increased from 0.1 to 5.0 in./sec the energy required to remove a given volume of rock increased by nearly 60 percent. Studies by the Japanese (13) indicate a similar phenomenon relating bit wear to cutting speed. That is, as speed increases, the wear or loss of material from the bit per unit volume of rock removed increases. Also since deep cuts have proportionately less wear per unit volume of rock removed in addition to requiring less energy per volume, it appears that deep cuts at low speed is the most promising mode of operation for a boring machine.

2.9 Effect of Rock Properties

Emphasis in boreability prediction has been in the past centered on relating the ease of cutting a particular rock to the more commonly used physical properties of the rock. Although some success has been achieved in correlated compressive strength to boreability, its application is quite limited. The problem is in not considering factors such as grain size, flaws, chipping mechanisms and specific energy. Work will continue in an attempt to relate boreability to the more common and easily obtained physical properties, but it is felt that the most valid approach is the actual cutting of the rock in the laboratory and relating the results to field boring.

2.10 Scaling Relationships

The use of the above mentioned laboratory linear cutting results for prediction of field boring performance in a particular rock type will require development of the scaling relationships that account for the differences in size and forces.

Some work (8) has been done in respect to scaling factors, but is incomplete and not totally applicable to rock boring. One of the main purposes for construction of the large linear cutting machine was to allow full scale tests for comparison to results from the small linear cutting machine. From this comparison it is hoped to develop the size and force scaling relationships between the two linear cutting machines. This, in turn, can be used in predicting field boring performance.

3. CONCLUSIONS

Valuable information has been gained from previous work performed in various fields relating to the problem of rock boring. Much progress has been made toward an understanding of rock failure under cutters. However, as yet no one has been able to relate this information to prediction of field boring performance. Also even with the apparent differences in efficiencies of the different cutter types, no meaningful and direct comparison of the applicability of the respective types has been made to date. It appears the best way to eliminate this gap in the knowledge is through extensive tests with the small and large scale linear cutting machines and by using various cutter types for these tests.

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